NASA Contractor Report 198347

Novel Composites for Wing and Fuselage Applications

Task 1 -- Novel Wing Design Concepts

J. A. Suarez, C. Buttitta, et al.
Northrop Grumman Corporation, Inc.
Bethpage, New York 11714

Contract NAS1-18784

July 1996

National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

FOREWORD

This Final Technical Report covers the work performed under Contract No. NASI-18784 in Task 1 – Novel Wing Design Concepts – from May 1989 through September 1991. The work was accomplished by Grumman Aircraft Systems, an Operating Division of Grumman Corporation, Bethpage, New York, and its subcontractors, Textile Technologies, Inc. and Compositek Corporation, under the sponsorship of NASA Langley Research Center "Novel Composites for Wing and Fuselage Applications."

The work was administered under the technical direction of Mr. H. Benson Dexter, NASA/LaRC Contracting Officer Technical Representative.

Key Grumman personnel associated with the program, and their respective areas of responsibility include:

• Grumman Corporation	
J. Suarez	Program Manager
C. Buttitta	Structural Mechanics
G. Flanagan	Structural Mechanics
T. DeSilva	Structural Design
W. Egensteiner	Structural Analysis
J. Bruno	Weight Optimization
J. Mahon	Advanced Materials and Manufacturing
C. Rutkowski	Tooling
R. Collins	Quality Control
R. Fidnarick	Elements and Material Test
• Textile Technologies, Inc.	
J. Maiden	Woven Preforms
• Compositek Corporation	
J. Neves	RFI Process

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1 – INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

1.1.1 Program Objectives

The primary objective of the Novel Composites for Wing and Fuselage Applications Program (NCWFA) is the application of new materials, design concepts, and manufacturing processes to achieve the full potential of composite primary structures for transcentury aircraft. This effort is geared to overcoming deficiencies in state-of-the-art composite materials such as their low damage tolerance, low fracture toughness, low notch strength, and low out-of-plane strength, as well as the materials' high acquisition and manufacturing costs which have contributed to the lack of widespread production commitments to advanced composite structures.

In Task 1 – Novel Wing Design Concepts – the objective was to conduct design trade studies to arrive at advanced wing designs that integrated new material forms with innovative structural concepts and cost-effective fabrication methods. A representative spar was selected for design, fabrication, and test to validate the predicted performance. Textile processes such as knitting, weaving, and stitching were used to produce fiber preforms that were later fabricated into composite spars through epoxy Resin Transfer Molding (RTM), Resin Film Infusion (RFI), and consolidation of commingled thermoplastic and graphite tows. The target design ultimate strain level for these innovative structural design concepts was 6000 μin./in. The spars were subjected to four-point beam bending to validate their structural performance.

1.1.2 Program Definition

This program, Task 1 – Novel Wing Design Concepts, was divided into the following five major subtasks:

- Subtask 1: Wing Design Trade Studies
  - Selection and approval of baseline aircraft
  - Multi-spar wing configuration
  - Multi-rib wing configuration
  - Material/configuration concepts
  - Concept evaluation
- Subtask 2: Intermediate Wing Y-Spar Design
  - Woven commingled preforms
  - Woven/stitched preforms
  - Knitted/stitched preforms
- Subtask 3: Fabrication of Y-Spars
  - Woven and stitched IM7 preform processed by RTM
  - Woven and stitched IM7 preform processed by RFI
  - Woven and stitched AS4/PEEK commingled preform autoclave consolidated
  - Knitted and stitched G40-800 graphite preform processed by RTM
  - Knitted and stitched G40-800 graphite preform processed by RFI

- Subtask 4: Tests
  - Material properties tests
  - Tests of Y-spars
- Subtask 5: Assessment
  - Structural performance evaluation
  - Manufacturing evaluation.

1.2 SUMMARY

Task 1, Novel Wing Design Concepts, was a five-subtask, 29 month effort. First, following NASA approval of the proposed baseline wing, design trade studies were conducted to arrive at advanced wing designs that integrated new material forms with innovative structural concepts and cost-effective fabrication methods. The focus was on minimizing part count (mechanical fasteners, clips, number of stiffeners, etc), textile reinforcement concepts that provided improved damage tolerance and out-of-plane load capability, low-cost resin transfer molding processing, and thermoplastic forming concepts. The candidate structural concepts were rated on the basis of weight, cost, damage tolerance/durability, risk, producibility, inspectability/accessibility, and repairability. The concepts that showed the highest rating were used for subsequent detailed design, analysis, and fabrication studies. Preferred concepts were selected for development in accordance with the Design/Manufacturing Integration (D/MI) Plan and NASA approval. In Subtask 2, a representative spar of the wing box concept selected was designed using textile processes such as knitting, weaving, and stitching to produce fiber preforms that can be fabricated into composite spars through epoxy resin transfer molding and consolidation of commingled thermoplastic/graphite tows.

In Subtask 3, state-of-the-art resin film infusable and resin transfer moldable epoxies and commingled graphite/thermoplastic materials were used to fabricate the composite spars. The specific materials and processes used to fabricate the composite spars were documented in the Materials Selection/ Processing (MS/P) Plan. A total of eleven Y-spars were fabricated by four different materials/processing methods. The Y-spars were fabricated using: (1) IM7 angle interlock 0-/90-deg woven preforms with ±45-deg plies stitched with Toray high-strength graphite thread and processed using RFI and 3501-6 epoxy; (2) G40-800 knitted/stitched preforms and processed using RFI and 3501-6 epoxy; (3) G40-800 knitted/stitched preforms and processed using RTM and Tactix 123/H41 epoxy and (4) AS4 (6K)/PEEK 150-g commingled angle interlock 0-/90-deg woven preforms with ±45-deg commingled plies stitched using Toray high-strength graphite thread and processed by consolidation.

In Subtask 4, Tests, a limited material properties database was generated for use in the design of the spars. A total of four Y-spars, one from each material form/process combination, were tested in four-point beam bending. The spar caps were stabilized with skin elements to allow flexure testing. Details of the tests were defined in the Structural Test Plan. Experimental test results were correlated with analytical predictions.

In Subtask 5, Assessment, the various material form/processing combination Y-spars were rated for their structural efficiency and acquisition cost. The acquisition cost elements considered were material, tooling, and labor.

2 - SUBTASK 1: WING DESIGN TRADE STUDIES

2.1 SELECTION AND APPROVAL OF AIRCRAFT

The baseline aircraft selected for this program with NASA approval is a subsonic patrol VSTOL aircraft, Grumman design 698-420. This design is a high-wing, T-tail, turn-tilting nacelle configuration which combines both powerplant and control vanes immersed in the fan stream, as shown in Fig. 1.

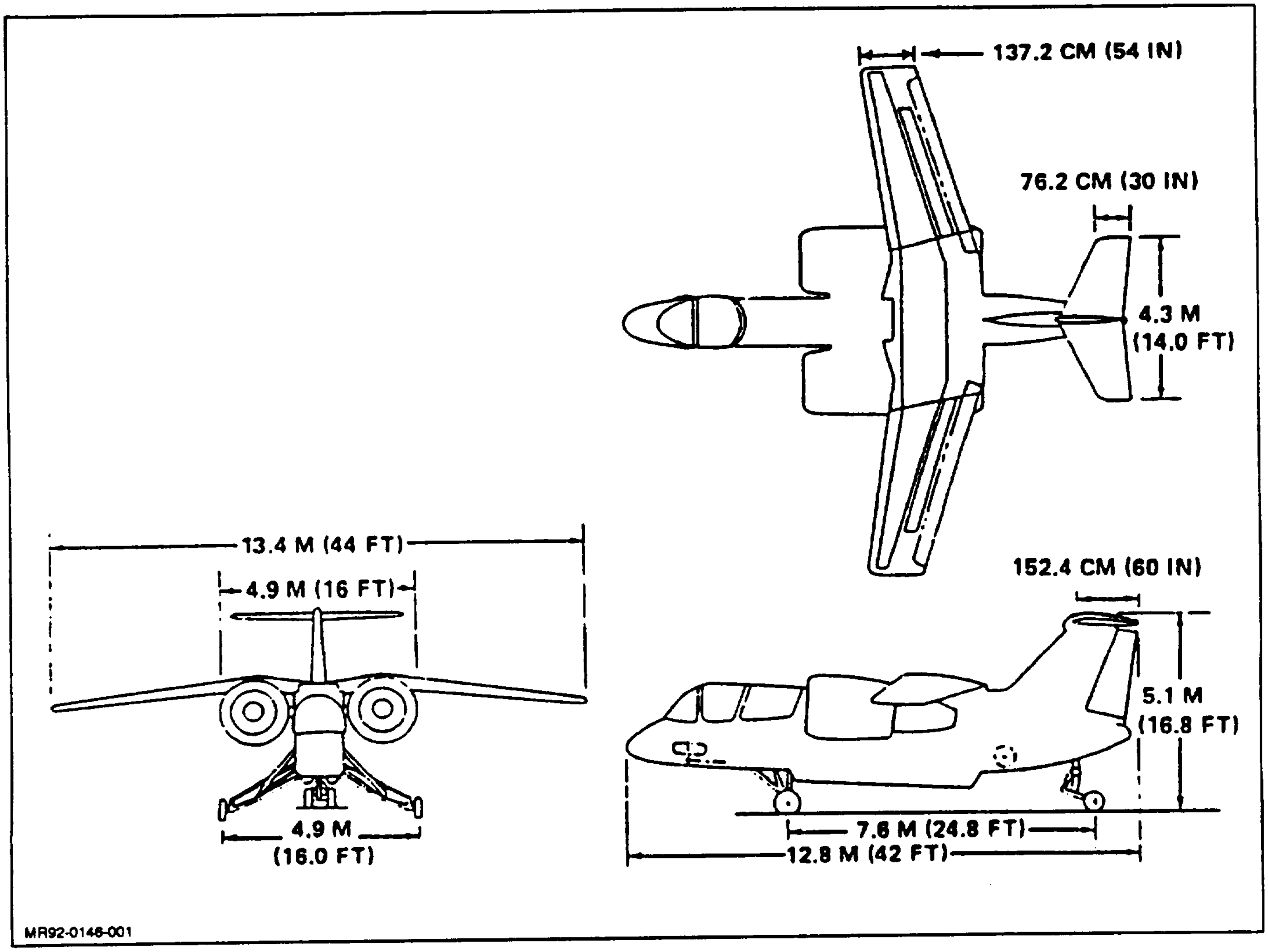

Fig. 1 Baseline Type D VSTOL Sea Control Configuration

2.2 GENERAL DESCRIPTION OF WING

The structural configuration for the wing is shown in Fig. 2. The wing has a span of 44 ft and a fold span of 16 ft, and is sized to allow installation of the conformal radar. The thickness ratio is 14% at the

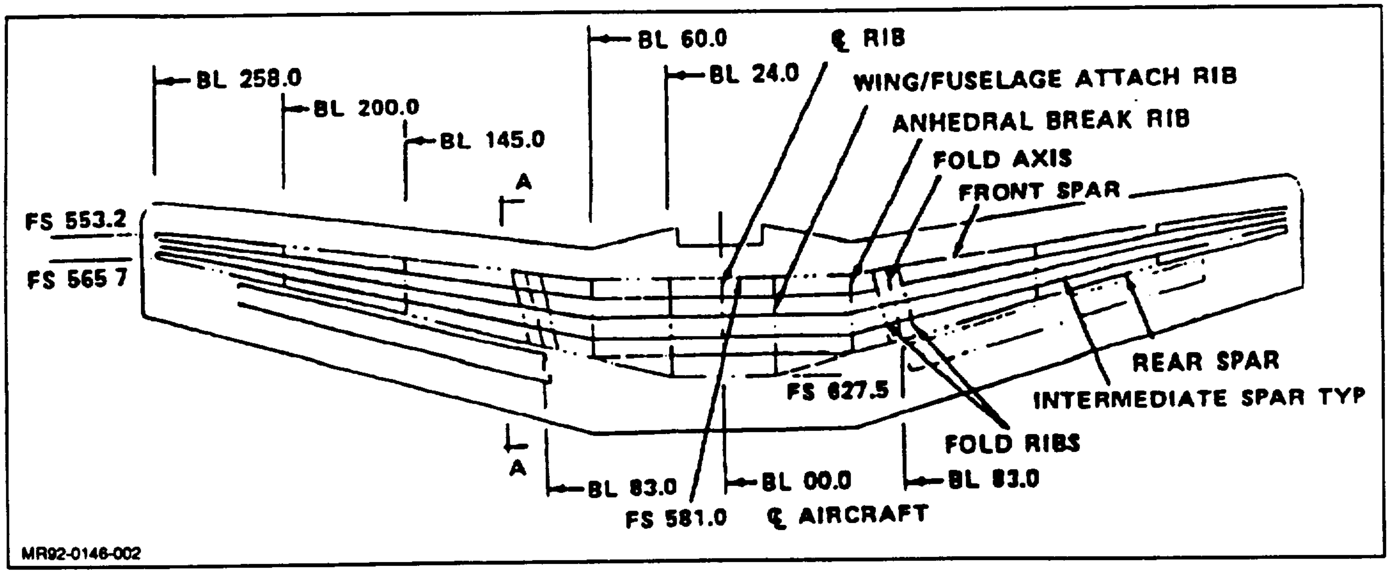

Fig. 2 VSTOL Wing Structural Configuration

root and 12% at the tip, with a maximum depth of 14.4 in. at the centerline. Fuel is carried in the wing box from fold-joint to fold-joint. Roll control in conventional flight is provided by spoilers mounted on the rear beam.

Consistent with the structural arrangement, design requirements, and advanced composite wing design technology, a baseline wing configuration was established from previous design efforts on the High Strain Wing Program. The upper and lower covers are Gr/Ep laminates, working to a design ultimate strain level of 6000 μin./in., and include Gl/Ep for softening strips and crack arrestment strips (for damage tolerance). The substructure consists of front, rear, and three intermediate spars. The spar webs are flat angle-stiffened Gr/Ep laminates, with the intermediate spars integrally co-cured and stitched (with Kevlar) to the lower cover. Gr/Ep sinewave ribs were used except at the wingfold and tip, where titanium and Gr/Ep plain panels were used, respectively. Figures 3 and 4 show the detailed structural arrangement.

2.3 TRADE STUDY CRITERIA AND DESIGN PHILOSOPHY

2.3.1 Static Loads

The composite wing structure is designed to simultaneously withstand the ultimate loads and other accompanying environmental phenomena without failure; this ensures the integrity of the structure under static load. Limit loads are maximum loads normally authorized for operation. "Design limit load" is the most critical of all design load conditions on the aircraft structural elements. Ultimate load is obtained by multiplying the "design limit load" by a safety factor of 1.5.

2.3.2 Maximum Strain Criteria

The use of high-strain technology has progressed to the point where increased structural efficiency and reduced weight have been demonstrated by increasing design ultimate strain levels by 50%, to 6000 μin./in. (Current design philosophy limits design ultimate strain to 4000 μin./in.) The design ultimate strain levels of the Novel Composite Wing concepts considered will therefore be maximized within the constraints of the design requirements to provide the greatest structural efficiency.

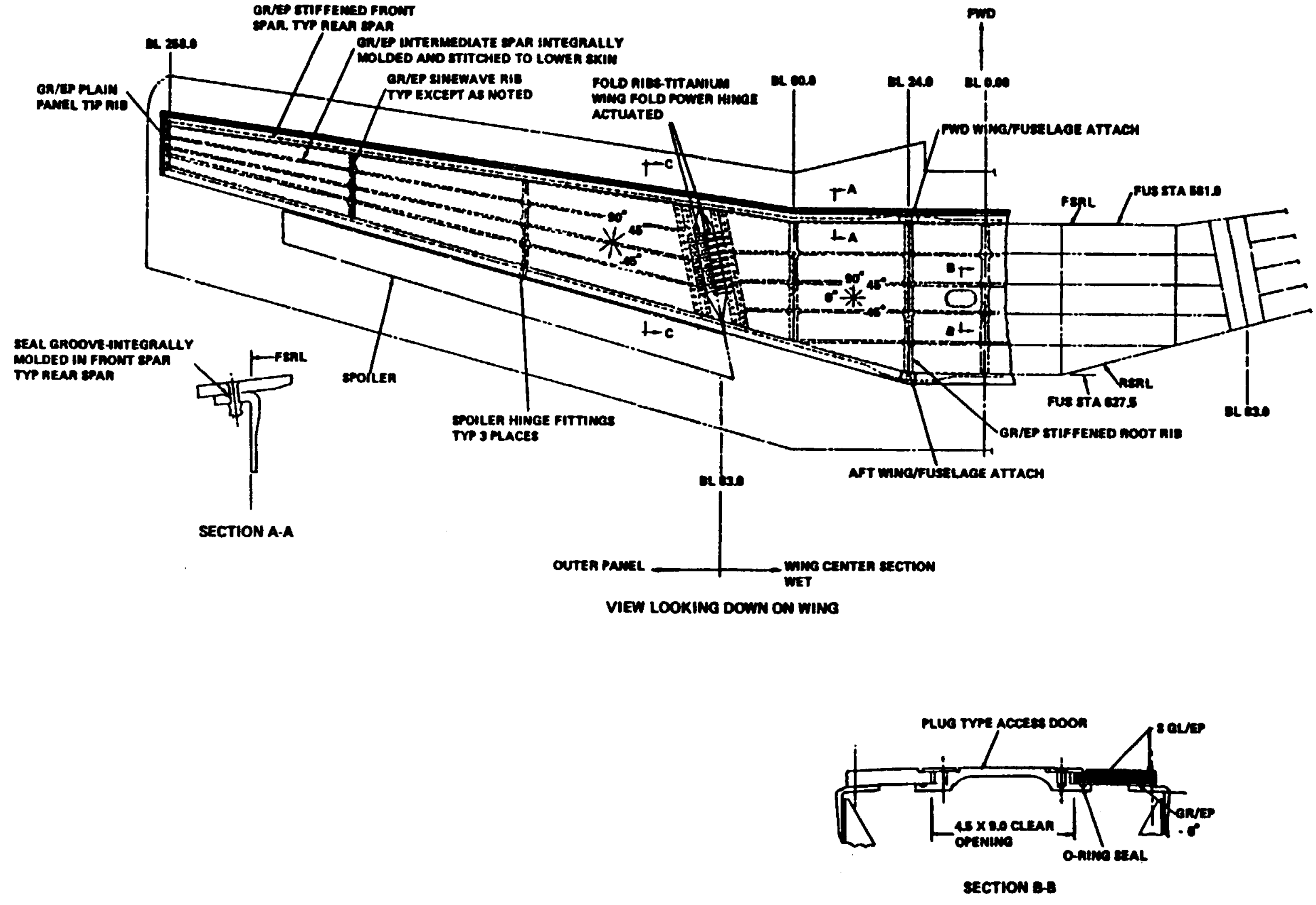

Fig. 3 Detailed VSTOL Wing Structural Arrangement

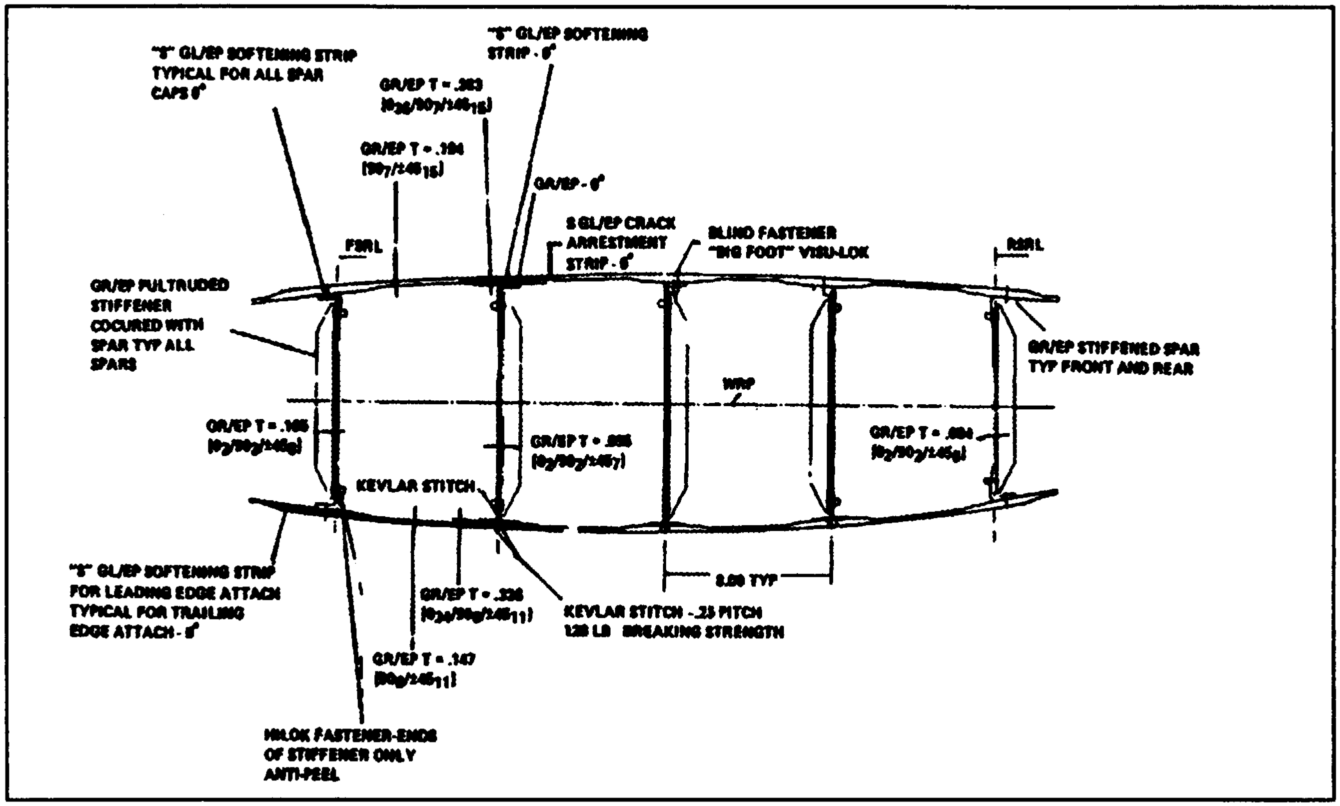

Fig. 4 Detailed VSTOL Wing Structural Arrangement (Section C-C)

2.3.3 Laminate Design Philosophy

Detail laminate design and overall structural design are integrated into the design iteration process. The basic material data, as shown in Table 1, are extended through classical lamination theory to predict multi-directional laminate behavior for uniaxial or combined loading.

It is our current practice to use the (0°/90°/±45°) family of laminates for reliable structural performance, and it is therefore applied to the Novel Composite Wing concepts. Careful attention is given to stacking sequence during the laminate design process since it plays a major role in creating an efficient and damage tolerant structure. The selected sequence places a pair (as a minimum) of ±45° layers at the surface with the smaller percentage of 90° layers immediately following. The required 0° layers and remaining ±45° layers are banded throughout the remaining laminate thickness. The total laminate is made symmetric and balanced with respect to its midplane.

Some of the structural reasons for the selected stacking sequence are:

- Placing ±45° layers at the surface provides moderately loaded plies for possible slight surface damage, maximum panel shear buckling, and a degree of damage tolerance
- Placing 90-deg layers close to the surface maximizes transverse bending stiffness for transverse loading paths
- Uniform dispersal of banded 0-deg and ±45-deg layers creates multiple shear paths for loading critical 0-deg layers, minimizes interlaminar shear stress concentrations, and provides a high degree of panel buckling stability.

2.3.4 Buckling

To optimize the composite structure from a weight viewpoint, the post-buckling capability of the materials must be utilized. The greatest buckling ratios permissible, within the constraints of aerodynamic considerations and minimizing of secondary load effects, are included in the design. The post-buckling capability of integrally cured cover and substructure configurations developed under the High-Strain Wing Program and other DoD-funded programs has been successfully demonstrated.

2.3.5 Environmental Conditions

Design allowables of composite materials are a function of moisture and thermal profile. For a typical external Gr/Ep laminate, a maximum equilibrium moisture content of 1.3% by weight or saturation at 79% relative humidity (whichever occurs first) is expected. Therefore, the resultant reduction in material properties is accounted for in the design process.

2.3.6 Durability

Since quantitative life prediction and demonstration is beyond the scope of the program, durability of advanced materials/structural concepts will be qualitatively assessed with respect to minimizing strain concentrations, notches, abrupt area changes, peel-prone joints, etc, and other factors as noted in MIL-A-87221.

2.3.7 Damage Tolerance

Damage inflicted on an airframe is usually identified as either accidental or combat. The degree of damage tolerance for our advanced concepts will be such that the vehicle can attain ultimate load with accidental damage and the highest load in the fatigue spectrum with current-day combat damage. Accidental damage is defined as that resulting from an equivalent impact energy level of 100 ft-lb or 0.1-inch indentation. An 8-in.-diameter hole is used as representative combat damage which covers a range of

TABLE 1 PRELIMINARY DESIGN PROPERTIES

PROPERTY	SYMBOL	IM7/8551-7A TAPE			G40-800/F584 TAPE			IM7/TACTIX 123		3-D WEAVE (1)	
		CTD	RTD	ETW	CTD	RTD	ETW	RTD		ETW	
								FIBER VOLUME FRACTION			
								.60	.56	.60	.56
LONGITUDINAL TENSILE MODULUS	E_1t, msi	24.7	24.7	24.7	27.2	27.2	27.2	20.5	19.1	20.5	19.1
LONGITUDINAL COMPR. MODULUS	E_1c, msi	23.5	23.5	23.5	23.9	23.9	23.9	19.5	18.1	19.5	18.1
TRANSVERSE TENSILE MODULUS	E_2t, msi	1.37	1.21	1.0	1.37	1.21	1.0	1.3	1.3	1.1	1.1
INPLANE SHEAR MODULUS	G_{12}, msi	1.08	0.76	0.67	0.92	0.65	0.50	0.73	0.73	0.50	0.50
EFFECTIVE SHEAR MODULUS FOR	G_{13}, msi	0.327	0.30	0.22	0.327	0.30	0.22	0.30	0.30	0.22	0.22
BUCKLING	G_{23}, msi	0.049	0.045	0.033	0.049	0.045	0.033	0.045	0.045	0.033	0.033
LONGITUDINAL TENSILE STRENGTH	F_1tu, ksi	324	344	336	369	394	384	233	217	228	212
LONGITUDINAL COMPR. STRENGTH	F_1cu, ksi	188	186	115	210	208	128	147	137	112	104
TRANSVERSE TENSILE STRENGTH	F_2tu, ksi	7.7	8.6	7.0	5.0	6.5	5.0	6.0	6.0	3.5	3.5
INTERLAMINAR SHEAR STRENGTH	F_{isu}, ksi	13.7	13.7	7.7	13.7	15.4	8.7	14.0	14.0	9.6	9.6
MAJOR POISSONS RATIO	υ_{12}	.324	.345	.335	.32	.35	.35	.35	.35	.35	.35
PER PLY THICKNESS	t, in	.0052	.0052	.0052	.00524	.00524	.00524	–	–	–	–

ETW: 180°F AND SATURATION AT 79% RELATIVE HUMIDITY
(1) 5% TRANSVERSE REINFORCEMENT

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threats. Damage tolerance will be achieved by design, using a safe-life approach wherein the damage is arrested, contained, and repaired.

2.3.8 Fuel Containment

The fuel pressure in the wing is a combination of system pressure and pressure generated by rolling conditions. The center section of the wing box for each concept is designed to the loads generated by the ultimate fuel pressure, 1.5 x P_{Limit}, in conjunction with the in-plane loads. The design will be such as not to exceed a pressure of 4 psi. In accordance with MIL-A-8861A, a pressure of 1.33 x 4 = 5.3 psi (limit) was combined with 1g flight loads. Ultimate loads are 1.5 x limit for this condition.

2.3.9 Weight

The torque box weight summary, presented in Table 2, shows a high strain composite torque box weight of 806.2 lb which represents a 426.8 lb or 34% savings over the baseline metal torque box weight of 1233 lb. Following the analysis of the various configurations, weight summaries will be presented and compared with our baseline to examine additional weight savings through novel composite applications.

TABLE 2 HIGH-STRAIN WING TORQUE BOX WEIGHT SUMMARY

COMPONENT	WEIGHT, LB/AC
UPPER COVER	(293.8)
• BASIC INTERSPAR COVER	240.5
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.6
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	10.6
• DAMAGE TOLERANCE PENALTY (±45° Gl/Ep)	0
• SPAR CAPS (INCL WRINKLING PENALTY)	40.1
LOWER COVER	(224.1)
• BASIC INTERSPAR COVER	187.2
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.2
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	8.0
• DAMAGE TOLERANCE PENALTY (±45° Gl/Ep)	1.5
• SPAR CAPS (INCL WRINKLING PENALTY)	24.9
FRONT SPAR	(88.6)
REAR SPAR	(36.0)
INTERMEDIATE SPARS	(110.0)
RIBS	(52.2)
TOTAL TORQUE BOX	806.2

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2.3.10 Cost

Novel composite concepts, that satisfy structural integrity, durability, and maintainability requirements, must also be cost-competitive. All Grumman design/manufacturing programs are integrally involved with a design-to-cost philosophy, the key phases of which are: configuration, design, and manufacturing/production.

Concepts will be reviewed qualitatively from a producibility standpoint, which includes tooling costs, compatibility with automated layup and net trim molding, and assembling requirements. In general, this effort will attempt to reduce the use of costly materials, part/fastener count, manufacturing complexity, recurring tooling, and difficulty in performing inspection.

2.4 MATERIAL-ORIENTED DESIGN CONCEPTS

To achieve the objectives of the NCWFA Program, composite design concepts incorporated into the baseline wing were studied. These can be classified into two categories: multi-spar and multi-rib.

The concepts were sized on a multi-stationwise basis, calculating the minimum amount of material required to satisfy static strength and stability requirements. In addition, secondary loading effects induced by crushing and fuel pressure were accounted for. Chordwise cuts along the span were used to size the covers and substructure at BL25, 100, and 200. The internal member loads and basic geometry at each station-cut are presented in Table 3. H and W are the wing box height and width, respectively; b is the stiffener/spar spacing; q_{fs}, q_{rs}, and q_{is} are shear flows in the front, rear, and intermediate spars, respectively; and P is internal fuel pressure. The data at BL25 will be used to size the center section, with BL100 and 200 sizing the outer panel. It becomes possible to compare the various forms of construction on a common basis once the minimum weight design for each of the various structural concepts has been determined by utilizing the advanced composite design philosophy stated previously and the following criteria:

- No minimum EI or GJ requirements
- 50% reversal of loads for negative wing bending
- Cover strains limited to 6000 μin./in. (ultimate).

TABLE 3 INTERNAL DESIGN LOADS

					5-SPAR				MULTI-RIB			
BUTT LINE	H_{avg}, in.	W_{box}, in.	N_x, lb/in.	b, in.	N_{xy}, lb/in.	q_{fs}, lb/in.	q_{rs}, lb/in.	q_{is}, lb/in.	N_{xy}, lb/in.	q_{fs} lb/in.	q_{is}, lb/in.	P, psi
25	11.21	46.5	12872	9.2	952	1936	921	1015	1829	3965	1522	6
100	10.22	31.5	10032	8.0	833	1660	838	822	1306	2893	1027	0
200	7.93	19.5	2910	5.0	418	802	452	350	593	1326	452	0
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2.4.1 Multi-Spar Concept

For multi-spar construction, the wing covers are essentially plane and resist axial and shear loading developed by the applied air loads. The wing covers are supported by spars which run spanwise along the length of the wing and carry vertical and torsional shear. Ribs are basically used in this type of construction at points where local concentrated loads are being introduced into the box or in areas of major load redistribution.

Our multi-spar concept was derived from previous studies, which indicated a five-spar configuration to be the most efficient from both a weight and cost standpoint. A total of 15 ribs was used in our arrangement, which is illustrated in Fig. 2.

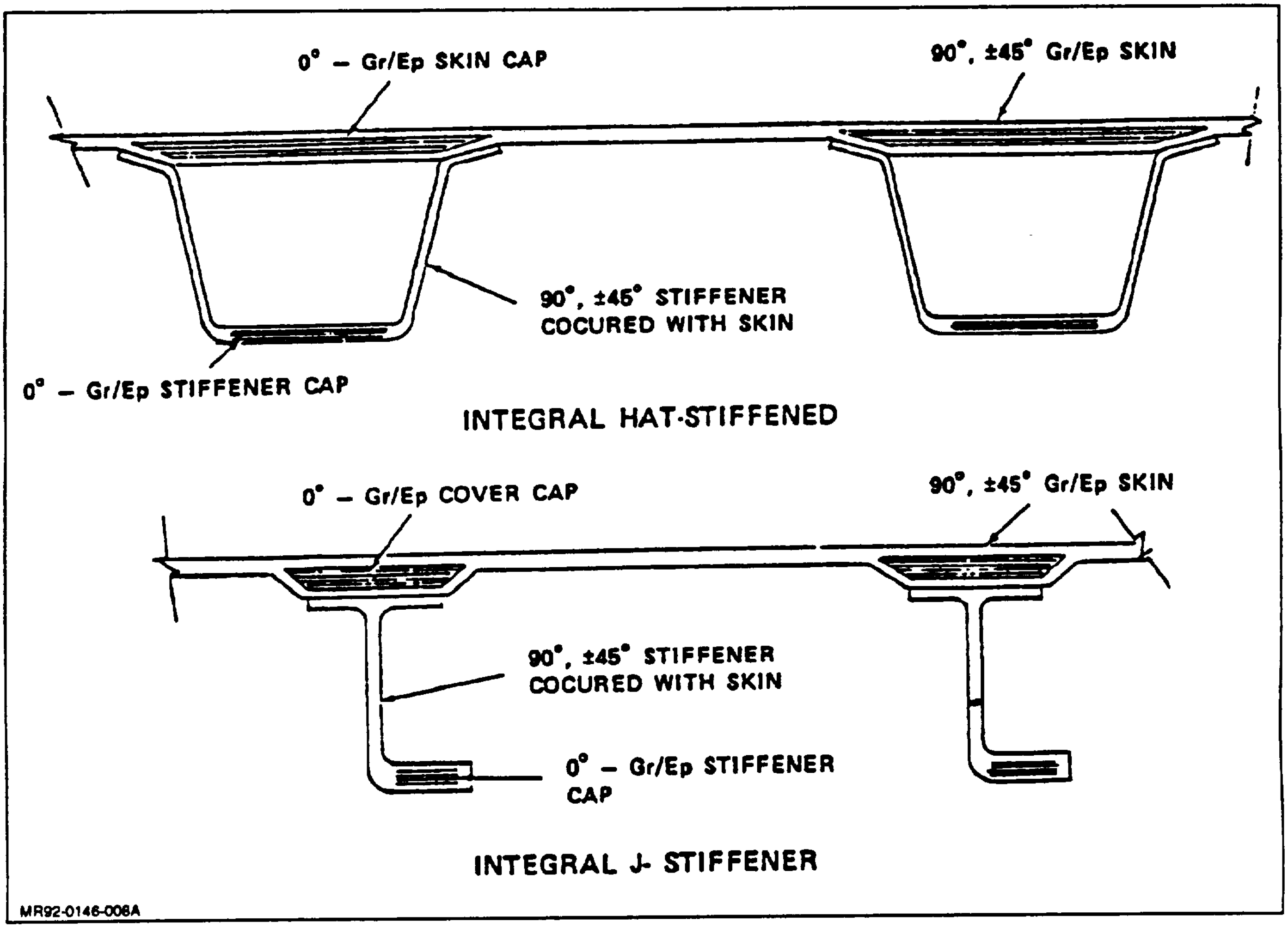

Fig. 5 Cover Concepts, Multi-Rib

2.4.2 Multi-Rib Concepts

In general, subsonic patrol aircraft wings are relatively thick where strength/stability conditions govern. Consequently, it is of interest to investigate cover configurations in which load-carrying material in the cross-section is redistributed to achieve increased flexural stiffness over that of the relatively uniform thickness cross-section multi-spar cover designs. This concept leads to the consideration of longitudinal stiffening systems as an integral part of the cover itself. The integral hat and open J stiffener configurations were considered in the study and are illustrated in Fig. 5 in combination with the skin. The designs are sized for all combinations of stiffener pitch equal to 4, 5, 6 and 7 in. and rib spacing equal to 15, 20, 25 and 30 in.

Because of its relatively high structural efficiency and potential ease of manufacture, stiffeners parallel to the front spar were selected as the preferred stiffener orientation. An illustration of each candidate stiffener orientation for 4, 5, 6, and 7 in. stiffener pitch is shown in Fig. 6 to denote the variation in structural density with the pitch change. It should be noted that the ribs shown are the basic ribs only.

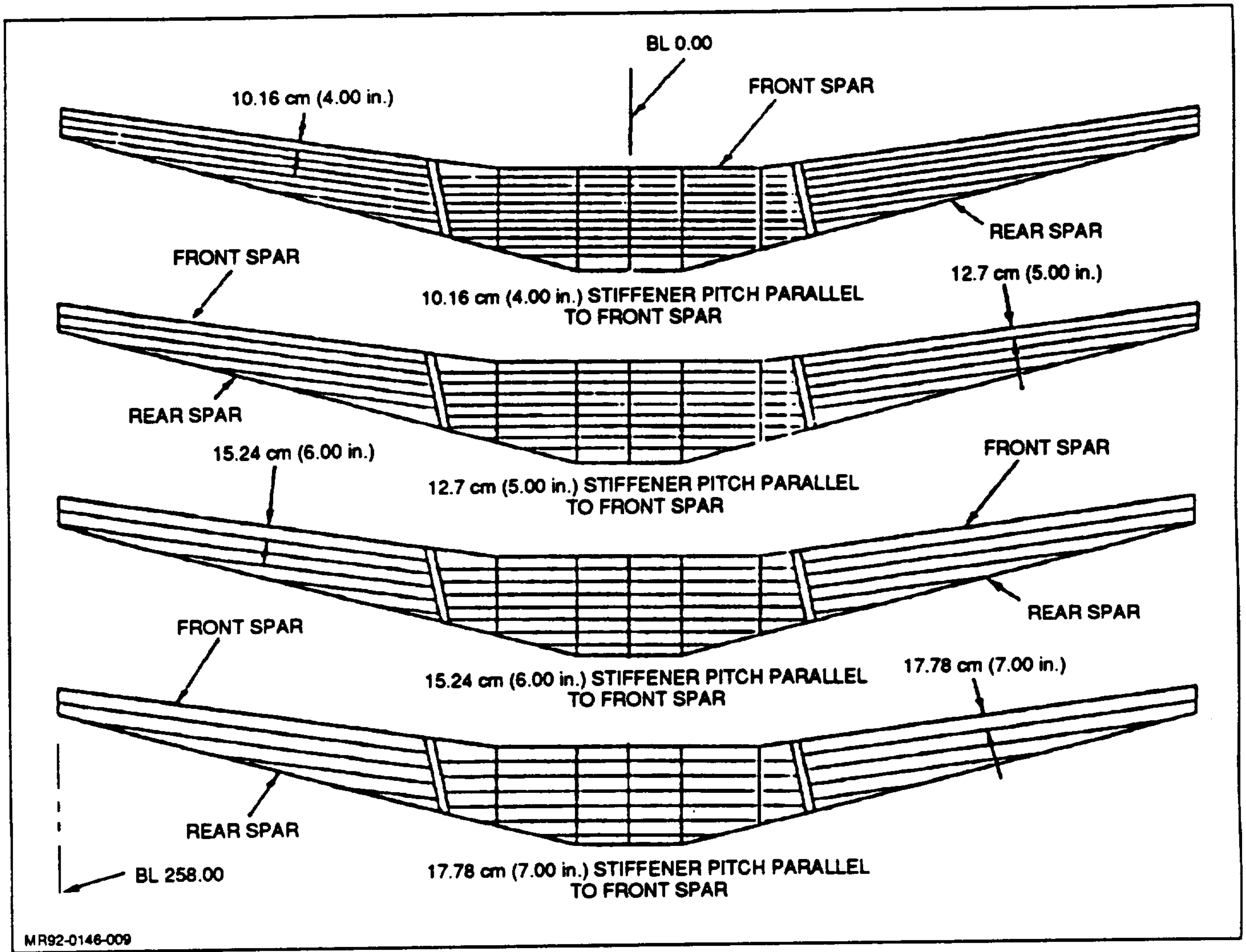

Fig. 6 Stiffener Orientation Parallel to Front Spar

Figure 7 illustrates the variation in structural density as a function of rib spacing. The solid lines in each configuration represent the basic ribs, while the broken lines represent the added ribs at the specified spacing. All added ribs shown are perpendicular to the front spar. The same front and rear spar configurations considered for the multi-spar design were also considered for the multi-rib designs. Also, the same damage tolerance applied to the multi-spar skin was applied to the multi-rib configurations.

2.4.3 Multi-Spar Cover Concepts

Two types of wing cover configurations were evaluated that have the potential for successfully increasing the working strain to levels at least 50% higher than those of the baseline. The two types evaluated (Fig. 8) were plain panel-spread and discrete cap. The first type, plain panel-spread, is essentially a monolithic skin of approximately constant thickness at any chordwise cut. In addition, the laminate is comprised of the same family of lamina orientations (0°, 90°, ±45°) at any point. The second type, discrete cap, utilizes a skin of two distinct laminate orientations. Between spars, the skin panel is composed of high strain-to-failure laminate of 90° and ±45° layers. The absence of 0° layers in this panel has two additional advantages: first, for a given thickness, it will possess a higher resistance to buckling

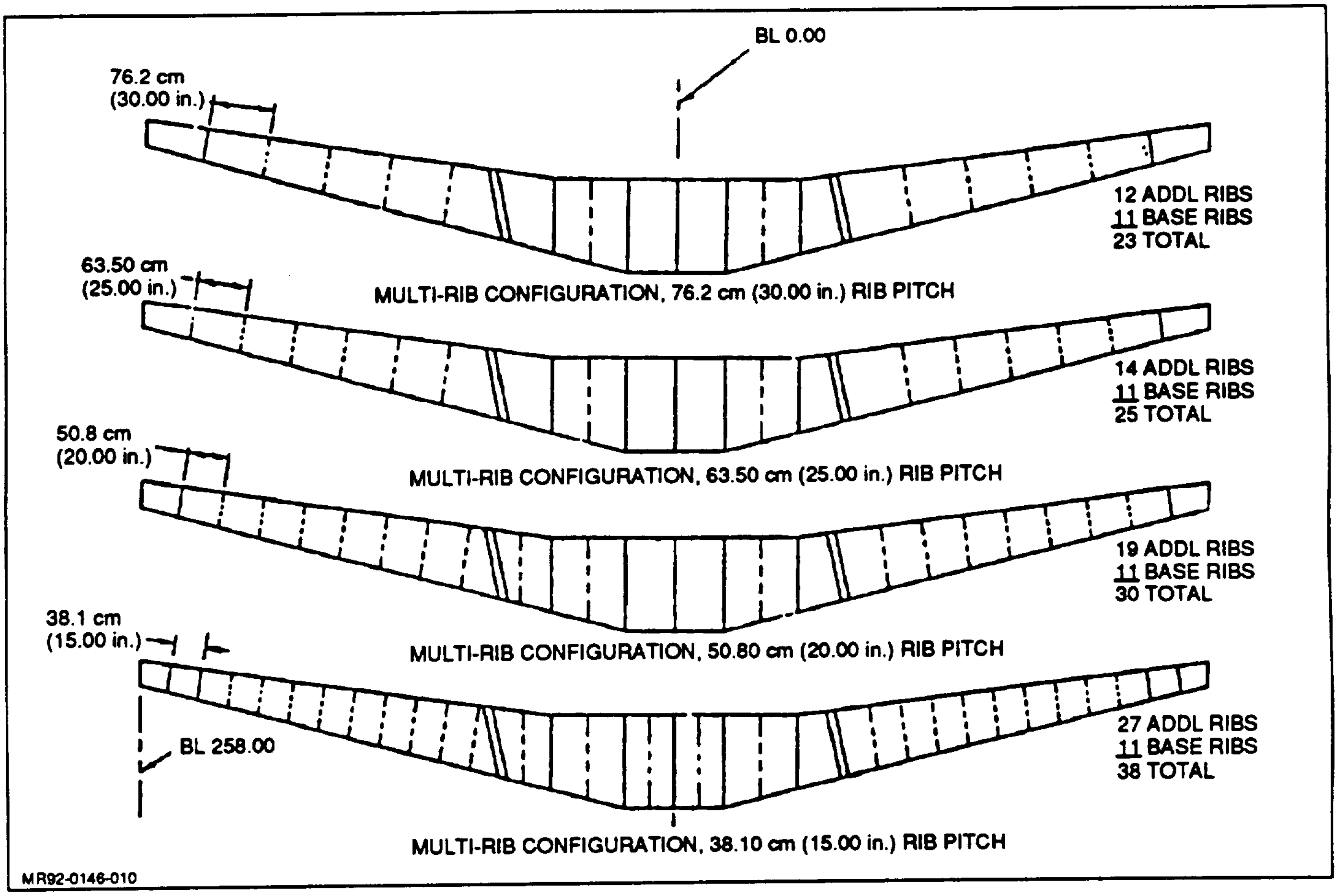

Fig. 7 Rib Pitch Configuration

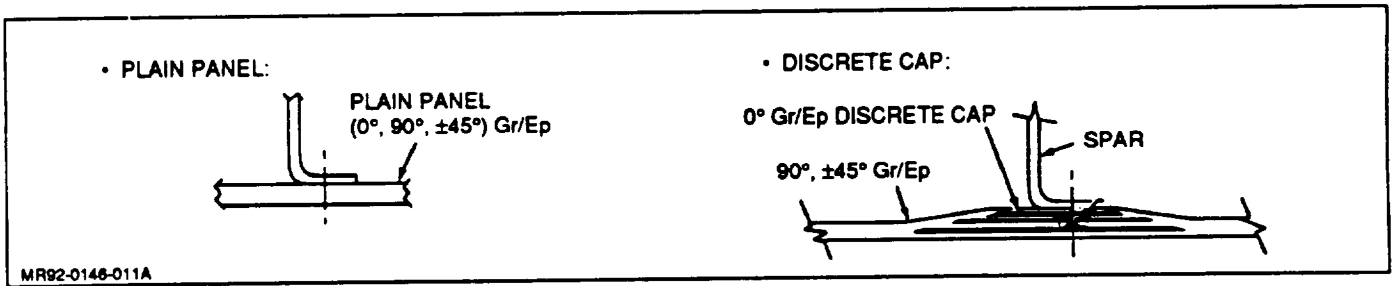

Fig. 8 Cover Concepts, Multi-Spar

loads; and second, the laminate's EA (extensional stiffness) is very low as compared to the total section, resulting in a lesser axial load applied to the unsupported segment of skin. At each spar 0° layers are added to the panel laminate, resulting in a local pad. The 0° layers provide the axial filament control to the laminate and carry the preponderance of axial load. Located over the spar, the high loads are rigidly supported to minimize any instability problems.

For each of the two configurations, two material systems were employed (IM7/8551-7A and G40-800/F584). The results of the tension and compression skin sizings are presented in Tables 4 and 5, respectively.

TABLE 4 TENSION SKIN SIZING RESULTS

CONFIGURATION	BL = 25 N_x = 12,872 lb/in. N_{xy} = 952 lb/in.	100 10,032 lb/in. 833 lb/in.	150 6361 lb/in. 650 lb/in.	200 2910 lb/in. 418 lb/in.	THEOR WT, lb
	t, in.*				
IM7/8551-7A 5 SPAR/30-10-60 LAM. PLAIN PANEL/UNBUCKLED	0.2652	0.2236	0.1664	0.1092	181.1
G40-800/F584 5 SPAR/30-10-60 LAM. PLAIN PANEL/UNBUCKLED	0.2600	0.2201	0.1624	0.1048	177.3
IM7/8551-7A 5 SPAR/DISCRETE CAP UNBUCKLED	0.2167	0.1804	0.1383	0.0927	149.0
G40-800/F584 5 SPAR/DISCRETE CAP UNBUCKLED	0.2096	0.1746	0.1318	0.0895	143.4
IM7/8551-7A 5 SPAR/DISCRETE CAP BUCK @ LL	0.1895	0.1592	0.1184	0.0801	129.9
G40-800/F584 5 SPAR/DISCRETE CAP BUCK @ LL	0.1802	0.1505	0.1158	0.0738	122.7

*t IS EQUIVALENT FLAT PANEL THICKNESS

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2.4.4 Multi-Rib Cover Concepts

The primary approach taken to achieve high strain capability in the design of the multi-rib cover concept was that of the integrally molded structure using IM7/Tactix 123 Gr/Ep, thereby eliminating or minimizing the effect of notches to accommodate spanwise fasteners, which would otherwise be required to attach the stiffeners to the covers.

The two stiffened cover configurations, hats and J's, that were evaluated represent closed- and open-section stiffening elements, respectively. Previous studies have demonstrated the merit of the closed hat stiffener in terms of structural efficiency and the ability to be integrally molded in a single autoclave operation. Even so, the open J was considered because of its potential for lower manufacturing costs.

The state-of-the-art regarding the performance of buckled composite skin panels in diagonal tension fields has progressed to the point where this type of structure appears to exhibit improved structural efficiency. Thus, each configuration was sized for two design considerations. The first condition considered all cover and stiffener elements unbuckled to ultimate load, while the second condition considered the effects of post-buckling by permitting the cover element between the stiffeners to buckle at limit load.

In both the hat and J stiffener configurations, the skin between stiffeners is fabricated using a laminate composed of 90° and ±45° layers only, with 0° layers concentrated in the skin over the stiffener. The advantages associated with this type of material distribution are:

- Most efficient 0° layers placement relative to bending strength requirements in conjunction with skin/stiffener column stability

TABLE 5 COMPRESSION SKIN SIZING RESULTS

CONFIGURATION	BL = 25 N_x = 12,872 lb/in. N_{xy} = 952 lb/in.	100 10,032 lb/in. 833 lb/in.	150 6361 lb/in. 650 lb/in.	200 2910 lb/in. 418 lb/in.	THEOR WT, lb
	t,in.*				
IM7/8551-7A 5 SPAR/30-10-60 LAM PLAIN PANEL/UNBUCKLED	0.3380	0.2860	0.2132	0.1352	230.1
G40-800/F584 5 SPAR/30-10-60 LAM PLAIN PANEL/UNBUCKLED	0.3328	0.2808	0.2096	0.1352	226.8
IM7/8551-7A 5 SPAR/DISCRETE CAP UNBUCKLED	0.2761	0.2335	0.1815	0.1207	190.4
G40-800/F584 5 SPAR/DISCRETE CAP UNBUCKLED	0.2661	0.2229	0.1744	0.1180	183.4
IM7/8551-7A 5 SPAR/DISCRETE CAP BUCK @ LL	0.2414	0.2020	0.1502	0.1049	165.9
G40-800/F584 5 SPAR/DISCRETE CAP BUCK @ LL	0.2292	0.1921	0.1478	0.0973	156.9

*t IS EQUIVALENT FLAT PANEL THICKNESS

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- Most efficient 0° layers placement for the local stability requirements with maximum loads concentrated on the smallest elements
- Minimum axial load on the skin element between stiffeners as a result of the absence of 0° layers.

Because of the large number of cover designs to be generated, design curves were developed to obtain structural sizes, gages, and weights in a timely manner. The STF67 program was used to develop the curves for the hat-stiffened configuration. The program optimizes the graphite/epoxy hat-stiffened section for local and overall buckling as well as strength. The resultant curves, shown in Fig. 9 and 10 using IM7/Tactix 123 Gr/Ep, are for the compression skin and tension skin, respectively. On these curves, a weight index is plotted against a structural index for stiffener spacings of 4, 5, 6, and 7 in. Therefore, given a particular loading (Nx), rib spacing (L), and stiffener spacing (b), a total weight (W) or smeared thickness (t) may be computed.

The J-stiffened skins were sized using the STF69 program. The program performs a strength/stability analysis of J-stiffened panels subjected to combined compression and shear, and a skin diagonal tension analysis. Curves similar to those generated for the hat stiffened skins were also developed for the J's and are shown in Fig. 11 and 12.

The various rib configurations considered are illustrated in Fig. 13 through 17. In addition to satisfying the crushing load requirement, the ribs were sized to include a 5 psi ultimate airload pressure distribution. The ribs were also permitted to buckle at limit load.

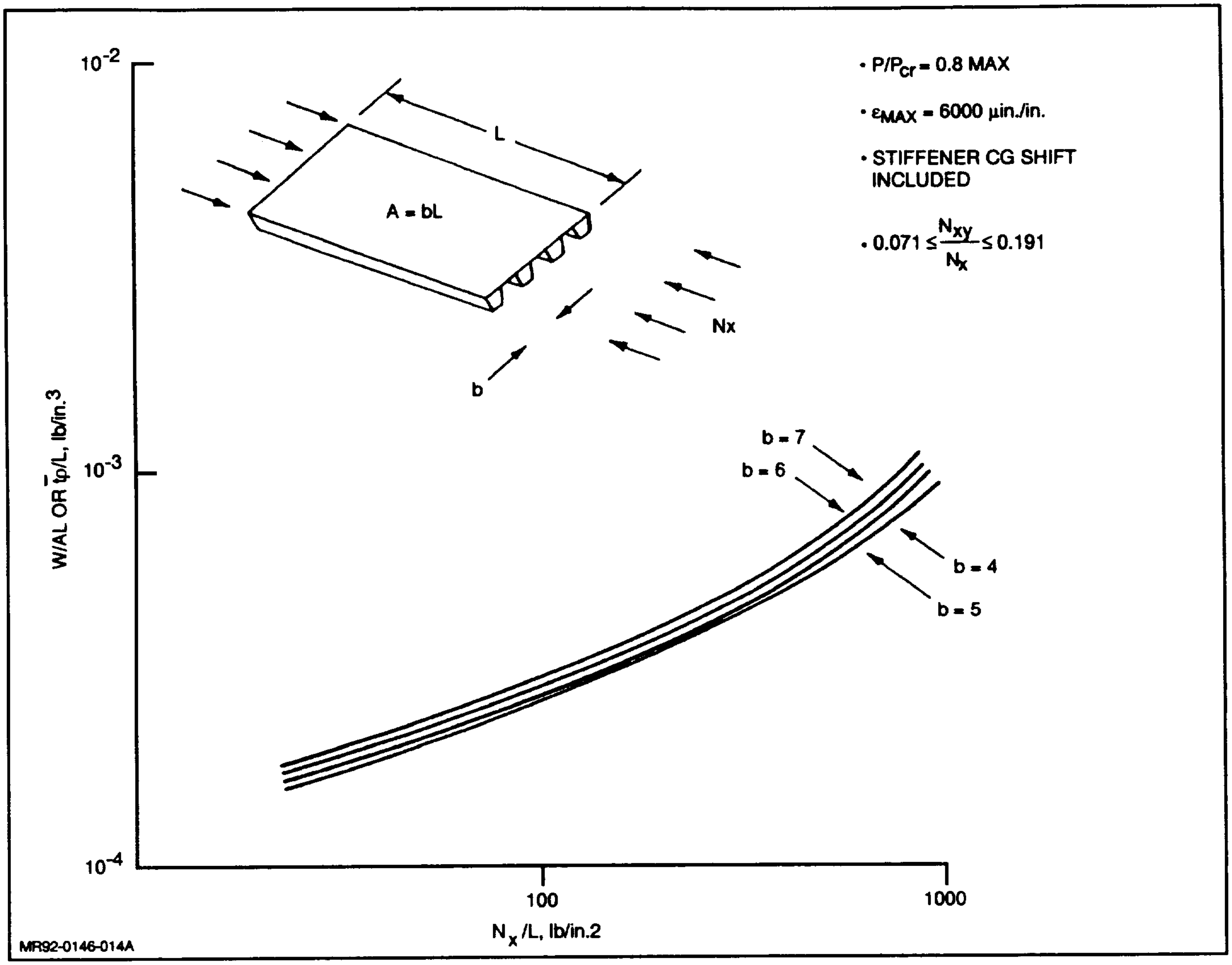

Fig. 9 Structural Index vs Weight Index for Unbuckled Gr/Ep Hat-Stiffened Panels

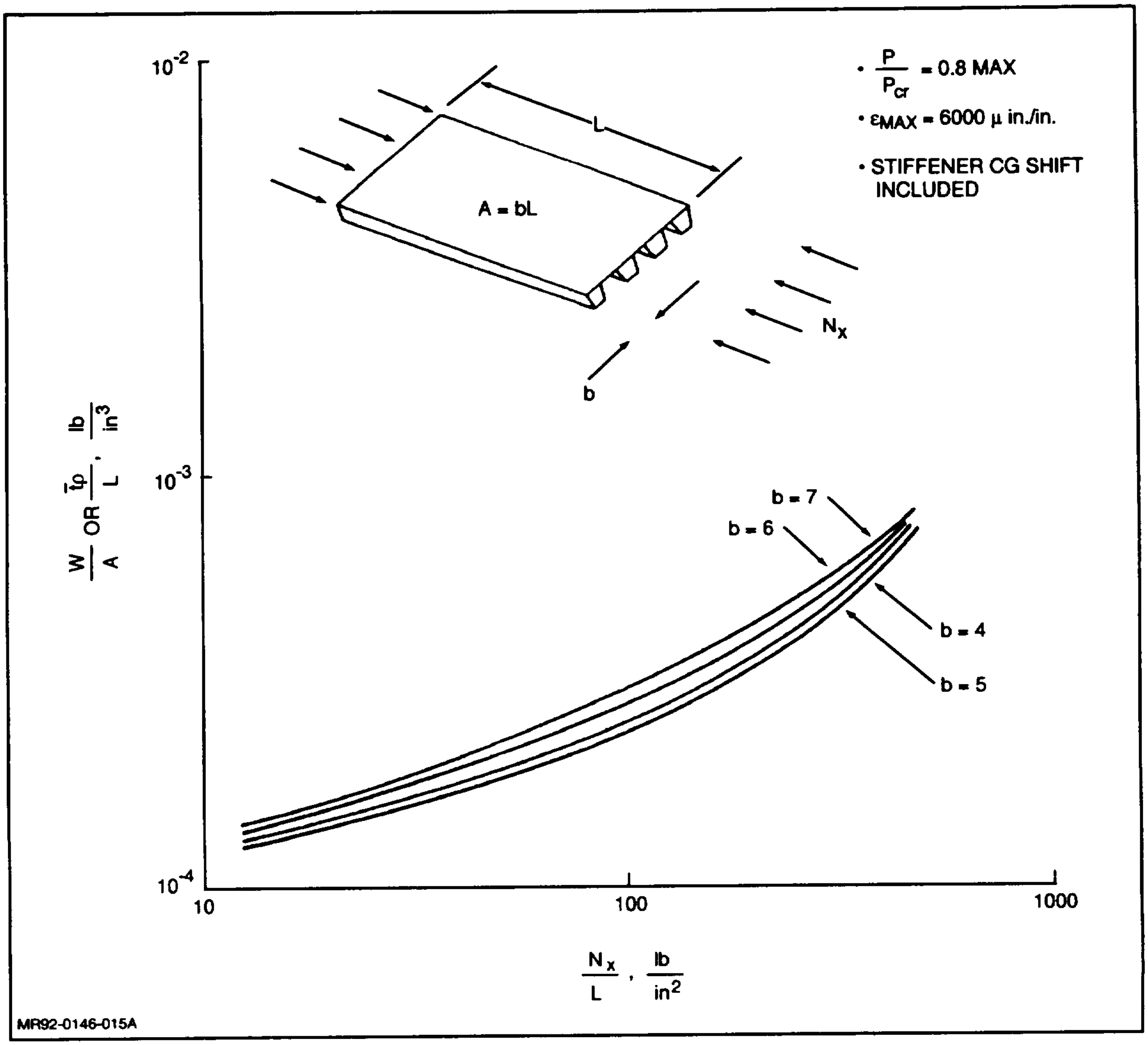

Fig. 10 Structural Index vs Weight Index for Unbuckled Gr/Ep Hat-Stiffened Panels in Tension with a 50% Reversal in Compression

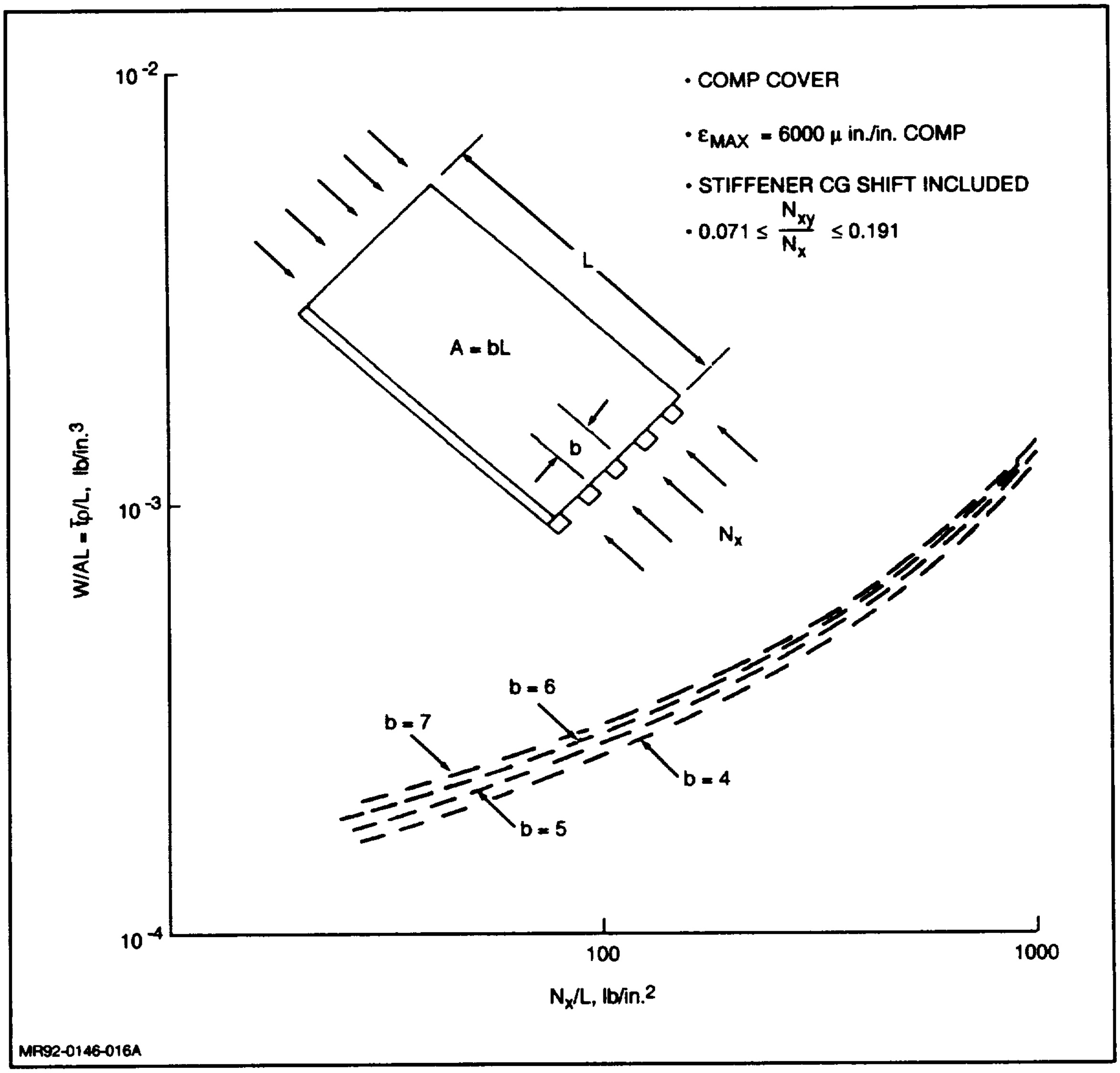

Fig. 11 Structural Index vs Weight Index for Unbuckled Gr/Ep J-Stiffened Panels in Compression & Shear

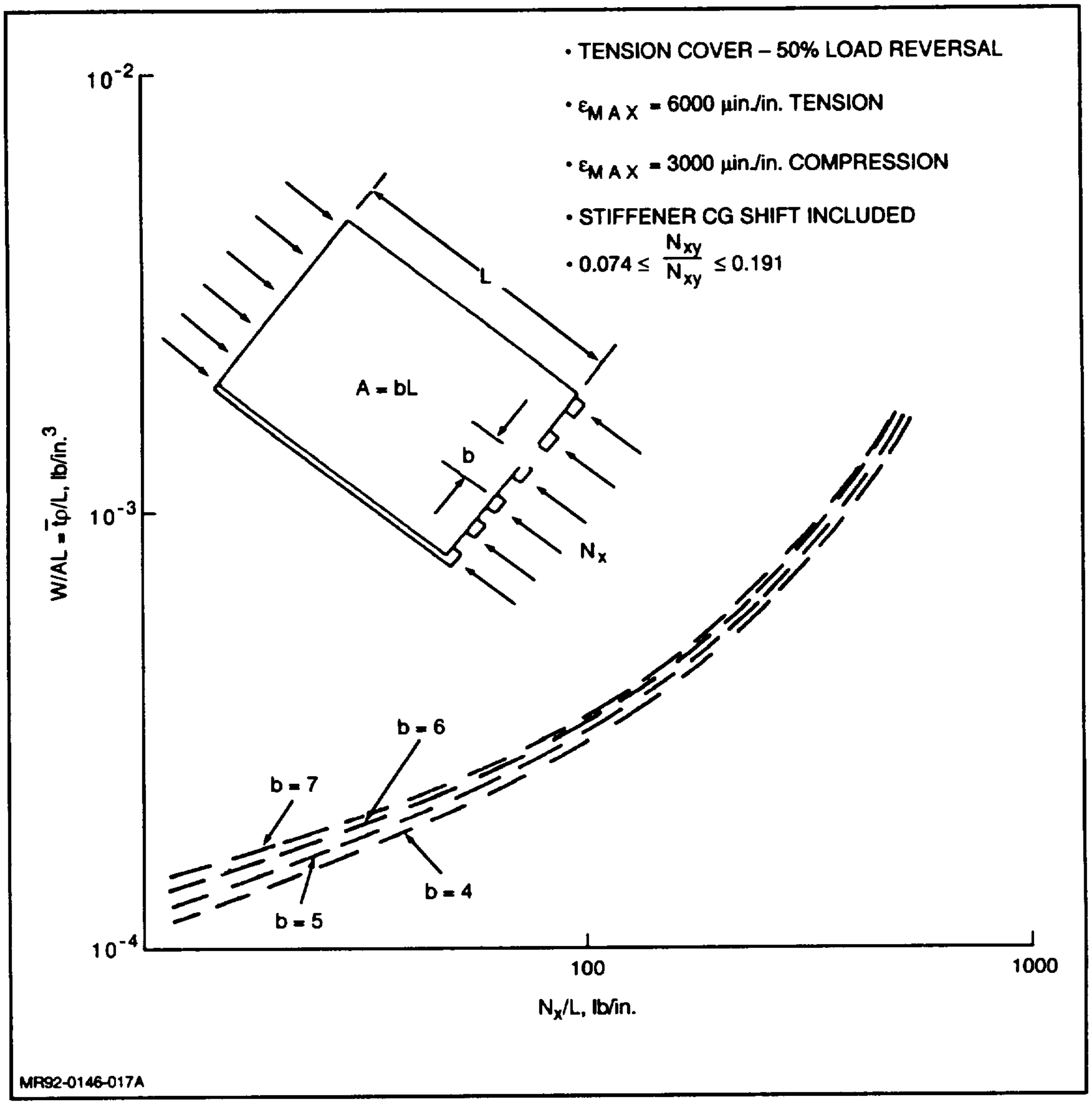

Fig. 12 Structural Index vs Weight Index for Unbuckled Gr/Ep J-Stiffened Panels in Tension and Shear with a 50% Reversal in Compression

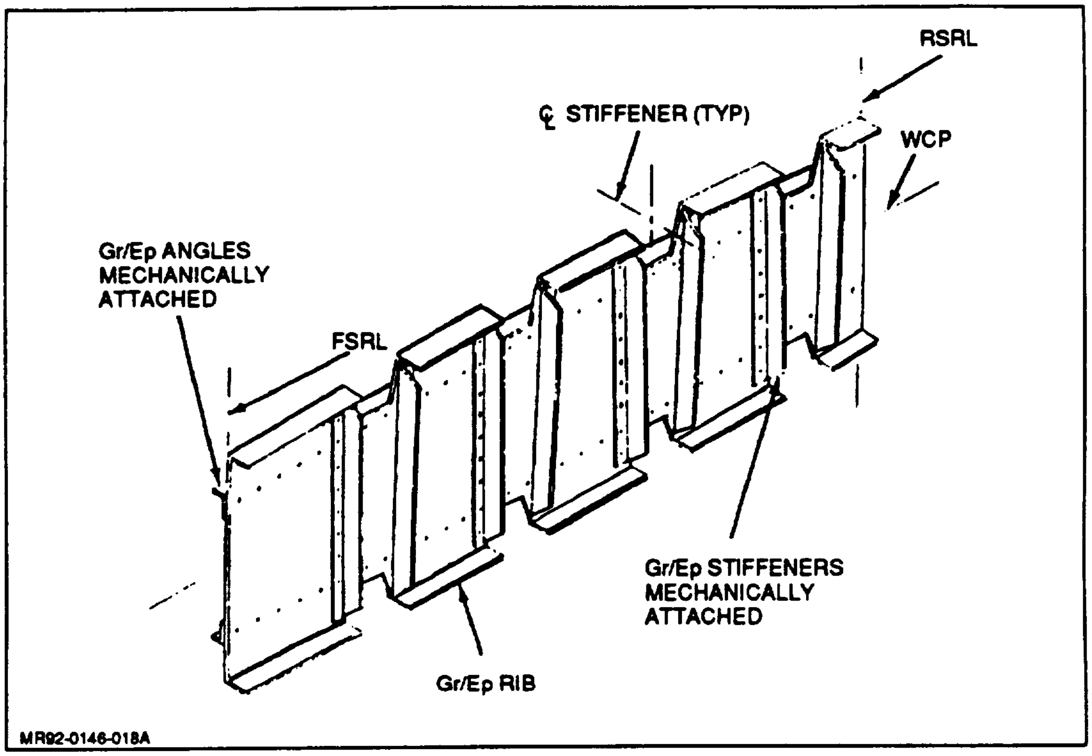

Fig. 13 Rib Concept, Multi-Rib

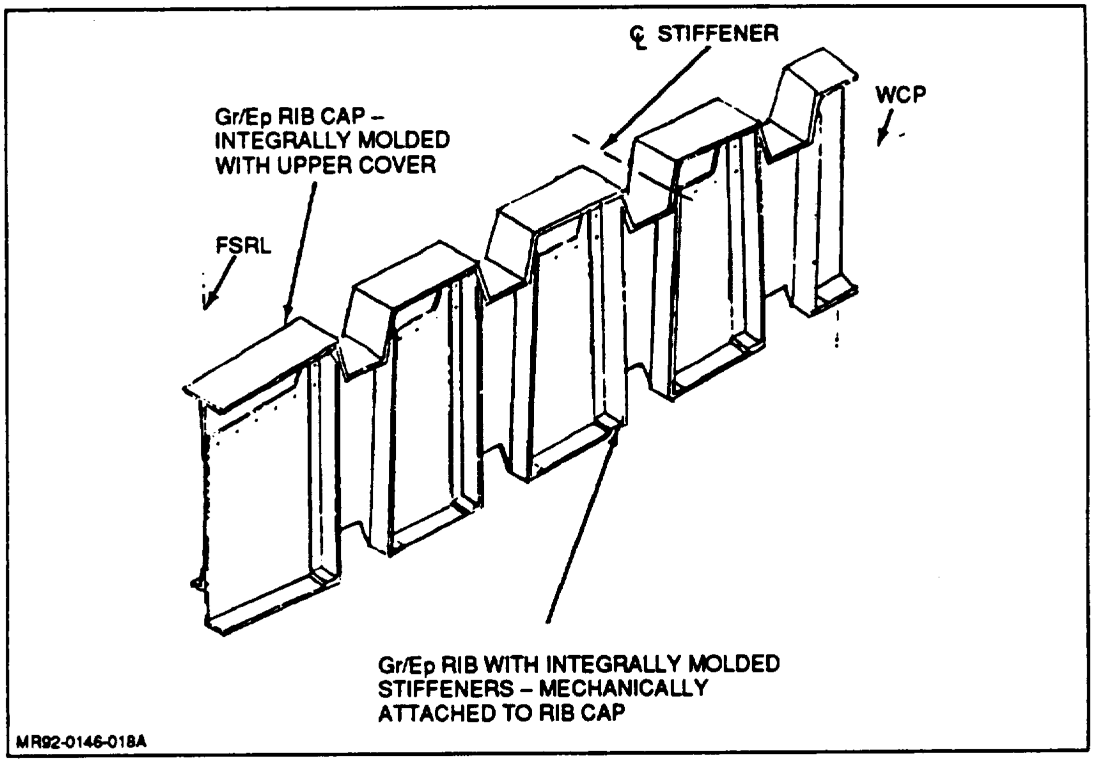

Fig. 14 Rib Concept, MultiRib

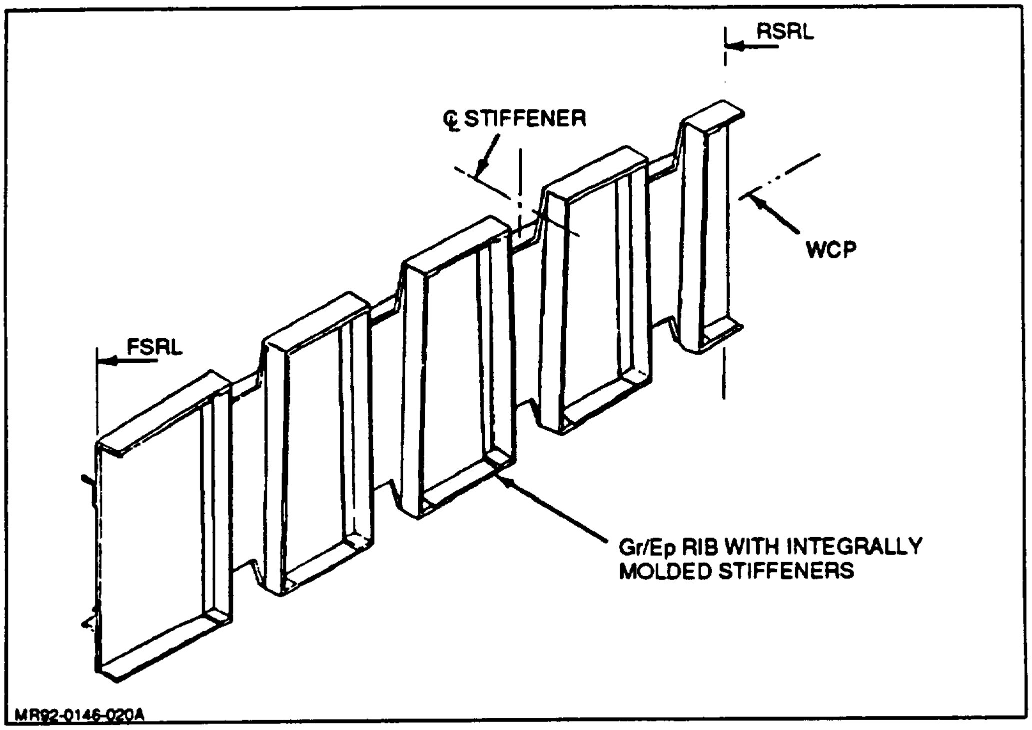

Fig. 15 Rib Concept, Multi-Rib

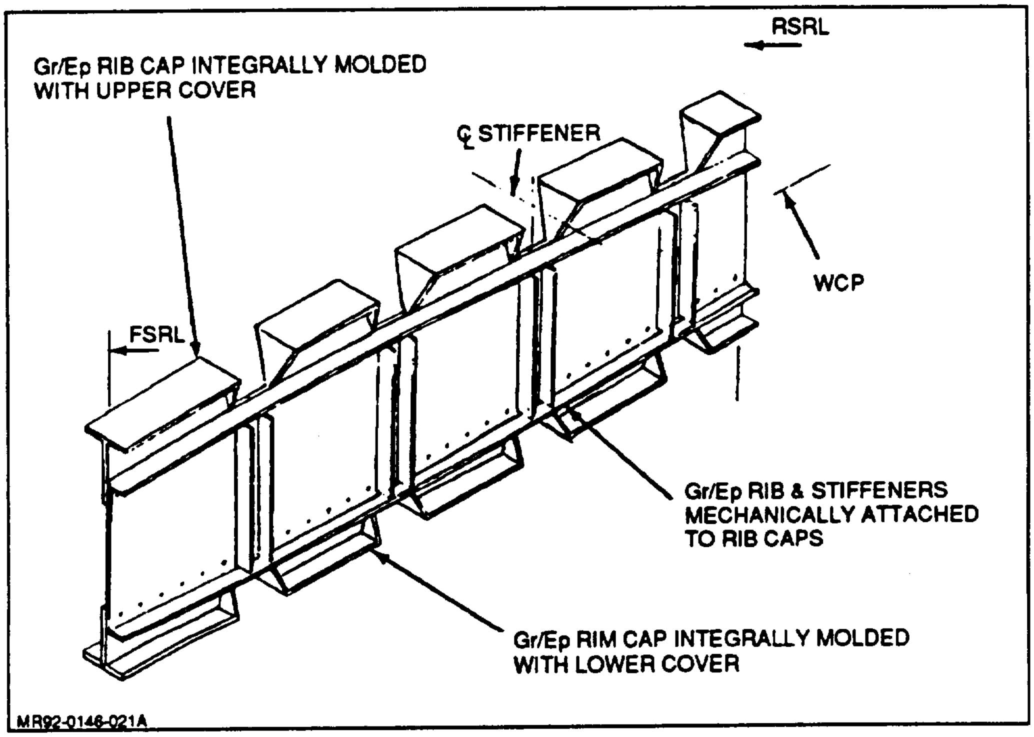

Fig. 16 Rib Concept, Multi-Rib

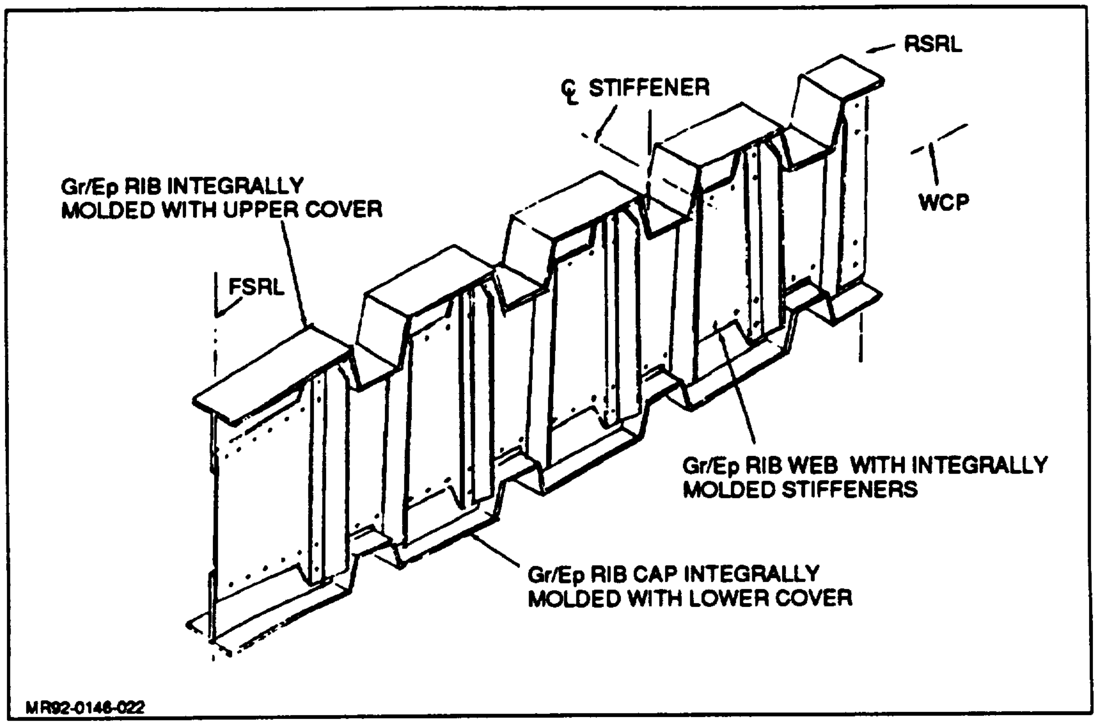

Fig. 17 Rib Concept, Multi-Rib

2.4.5 Spar Concepts

2.4.5.1 Spar Web Concepts – Design candidates investigated for the composite spar configuration are as follows:

- Unstiffened Flat Web (IM7/8551-7A)
- Angle Stiffened Flat Web (IM7/8551-7A)
- SynCore Stiffened Web (IM7/8551-7A)
- Sinewave Web (IM7/8551-7A).

Since it is our intent to determine realistic comparisons of designs that will support cover spanwise strain levels of approximately 6000 µin./in., analyses were performed to determine the relative efficiency of spar web designs under combined loading. The combined loading case addresses crushing loads associated with spanwise wing curvature and bending strain distribution on the web.

Sizing data of spar webs made from different structural materials or various forms of construction are presented as x-y plots of $N_{xy}/\bar{t}$ vs N_{xy}/b where:

N_{xy} = Ultimate Shear Flow, lb/in.
$\bar{t}$ = Effective "Smeared" Thickness of Web, in.
b = Spar Web Depth in.

Figures 18 and 19 show the efficiencies of the different configurations, covering the range of shear flows, with a maximum shear flow of 1015 lb/in. for intermediate spars and 1936 lb/in. for the front/rear spars. Although the sinewave web configuration is the lightest, its significantly higher production costs make the SynCore-stiffened web design more cost-effective.

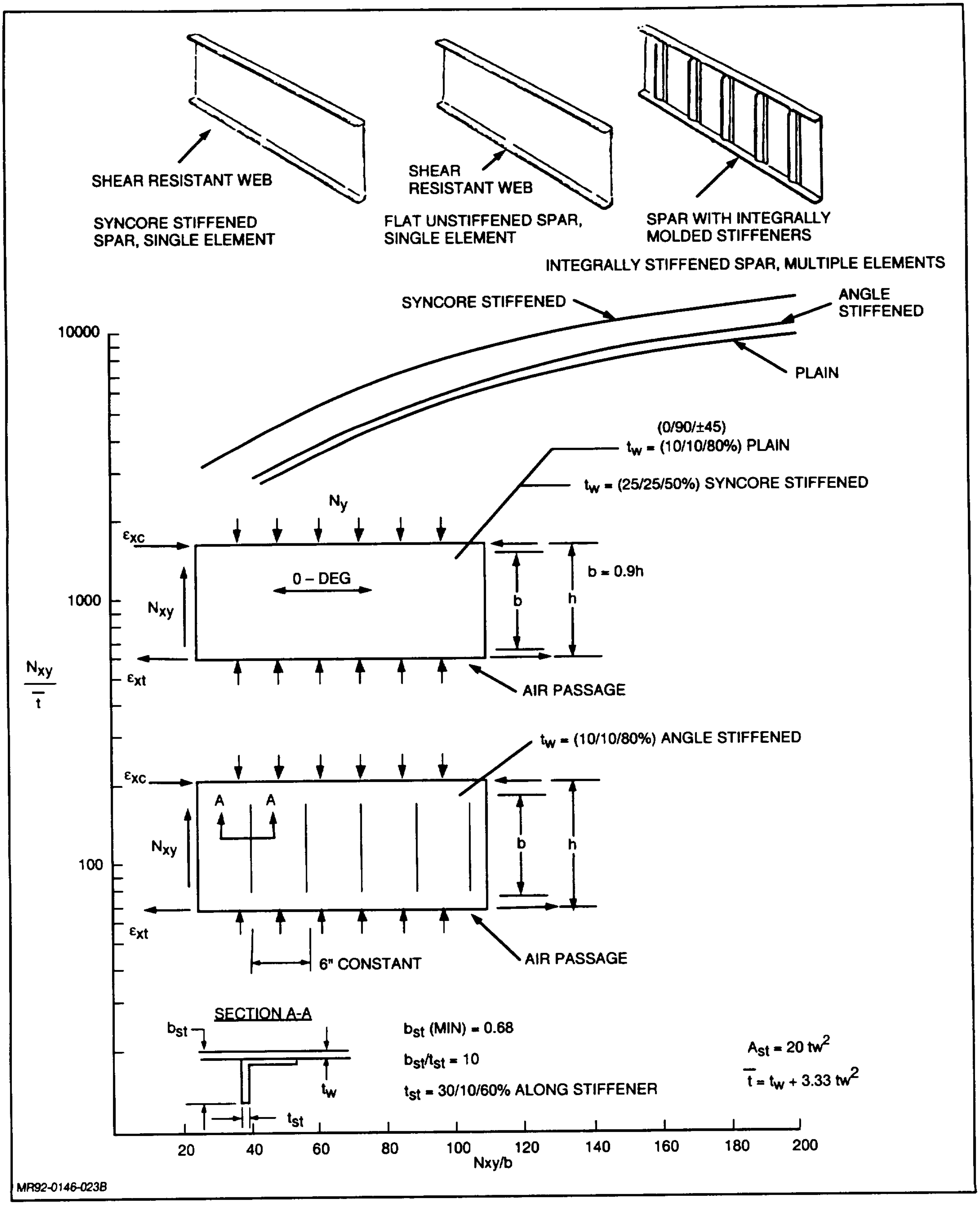

Fig. 18 Spar Web Efficiency

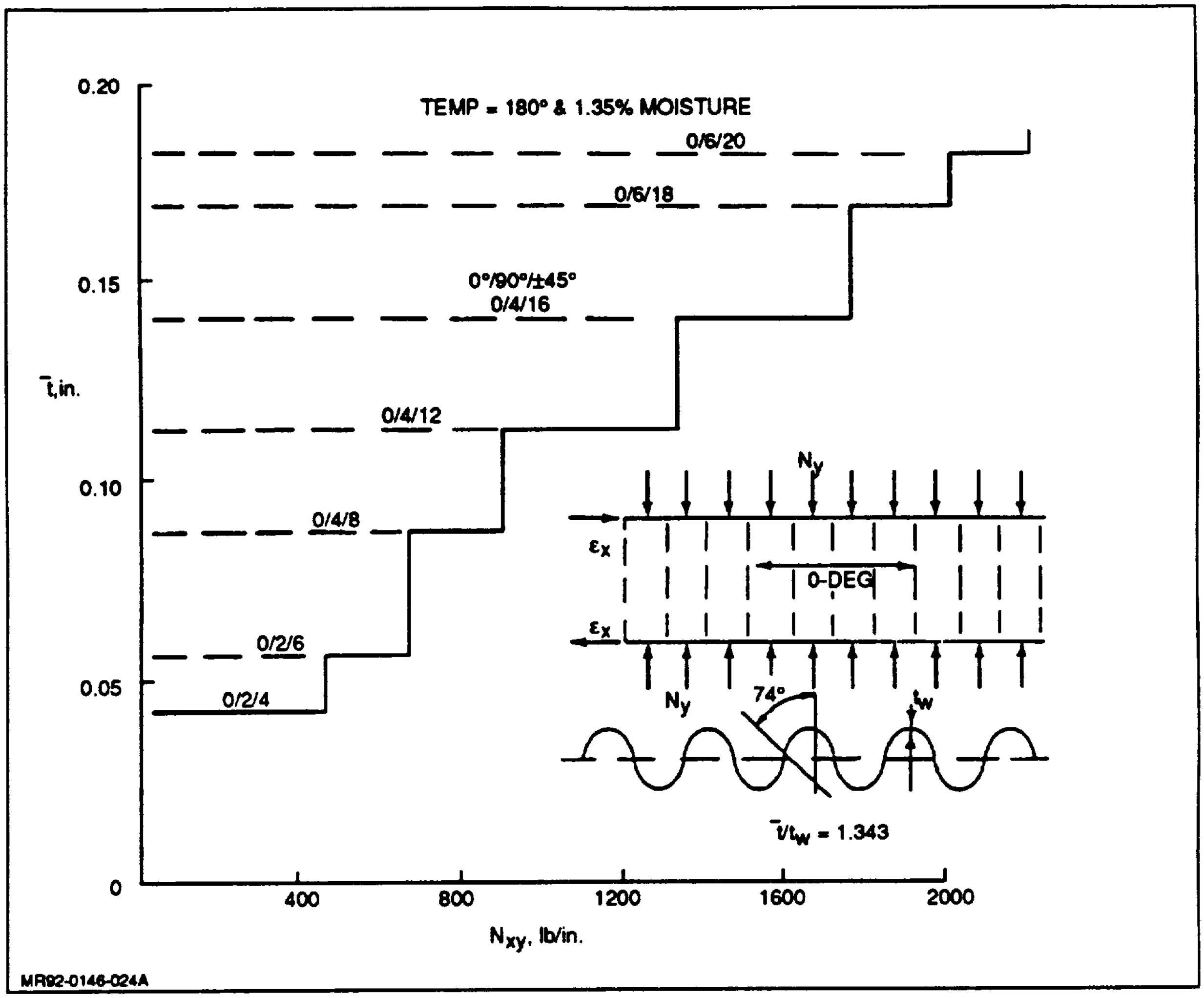

Fig. 19 Spar Web Efficiency (Sinewave)

2.4.5.2 Spar Cap Concepts – In order to support cover strains of approximately 6000 μin./in., a simplified analysis procedure was used to determine the thickness requirements of spar flanges with either "tee" or angle section attachment. The analysis considered:

- Foundation stiffness requirements of flange and web to preclude cover wrinkling failure
- Flange strength required for normal loads due to wrinkling and fuel pressure loading with regards to
  - Flange chordwise bending strength at the cover attachment line
  - Pull-through strength of flange at the cover attachment line
- Flange bearing strength for shear flow load transfer at the cover attachment line
- Minimum flange thickness requirement to preclude local buckling and inter-rivet buckling failure.

The flange thickness requirements for the various design configurations of the upper compression cover and lower tension cover, with 50% reversed wing normal bending moment, are summarized in Tables 6 and 7, respectively.

TABLE 6 SPAR FLANGE THICKNESS (IN.), COMPRESSION COVER

CONFIGURATION	BL	ANGLE			TEE		
		t_{wrink}	$t_{pull-thru}$	$t_{flange\ bend}$	t_{wrink}	$t_{pull-thru}$	$t_{flange\ bend}$
5-SPAR PLAIN PANEL	25	0.188	0.199	0.180	0.095	0.095	0.095
	100	0.174	0.174	0.156	0.088	0.088	0.078
	200	0.086	0.086	0.080	0.043	0.043	0.040
5-SPAR DISCRETE CAP	25	0.272	0.406	0.258	0.137	0.137	0.121
	100	0.239	0.239	0.196	0.120	0.120	0.098
	200	0.163	0.163	0.133	0.082	0.082	0.067
MR92-0146-025							

TABLE 7 SPAR FLANGE THICKNESS (IN.), TENSION COVER

CONFIGURATION	BL	ANGLE			TEE		
		t_{wrink}	$t_{pull-thru}$	$t_{flange\ bend}$	t_{wrink}	$t_{pull-thru}$	$t_{flange\ bend}$
5-SPAR PLAIN PANEL	25	0.079	0.079	0.097	0.040	0.040	0.058
	100	0.075	0.075	0.071	0.038	0.038	0.036
	200	0.058	0.058	0.056	0.029	0.029	0.028
5-SPAR DISCRETE CAP	25	0.115	0.115	0.121	0.058	0.058	0.068
	100	0.105	0.105	0.095	0.053	0.053	0.048
	200	0.089	0.089	0.081	0.045	0.045	0.041
MR92-0146-026							

2.5 COMBINED MATERIAL/CONFIGURATION DESIGN CONCEPTS

After completing the material-oriented design concepts, our efforts were directed toward developing combined material/configuration concepts. This involved the use of Y-spars and Y-stiffeners to support the covers. For the upper cover, the following concepts were studied:

1. Spread 0° supported by 5 or 6 Y-spars
2. Isolated discrete cap supported by 5 or 6 Y-spars
3. Isolated discrete cap supported by integrally cured Y-stiffeners.

The corresponding lower cover design configurations were as follows:

1. Spread 0° supported by 5 or 6 Y-spars
2. Isolated discrete cap supported by 5 or 6 Y-spars
3. Spread 0° supported by blade stiffeners.

Design ultimate internal member loads and basic geometry at each station-cut are given in Table 8. h and W are the wing box height and width, respectively, and b is the spar spacing. The following criteria were used to size the covers:

- No minimum EI or GJ requirements
- Maximum cover strain limited to 6000 μin./in. at ultimate load
- No cover buckling below limit load
- 50% load reversal for negative wing bending.

G40-800/F584 tape was used for the upper and lower covers and 3-D IM7/Tactix 123 weave was utilized to size the Y-spars. For the multi-spar concepts, only the intermediate spars were designed with the "Y" configuration. The SynCore-stiffened design was used for the front and rear spars.

TABLE 8 DESIGN ULTIMATE INTERNAL MEMBER LOADS

				5-SPAR		6-SPAR		MULTI-RIB
BUTT LINE	h_{avg}, in.	W_{box}, in.	N_x, lb/in.	b, in.	N_{xy}, lb/in.	b, in.	N_{xy}, lb/in.	N_{xy}, lb/in.
25	11.21	46.5	12872	9.2	952	7.4	904	1829
150	9.07	26.0	6361	6.5	650	5.0	617	970
200	7.93	19.5	2910	5.0	418	3.8	399	593

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A summary of the sizes obtained for the upper and lower covers are presented in Fig. 20 and 21, respectively. To provide a basis for comparison, the thicknesses reported represent the average or smeared thickness at a given station cut.

2.5.1 Multi-Spar: Intermediate Y-Spars

The basic philosophy in using intermediate Y-spars is that they reduce panel widths and required thickness on the upper cover. Although an increase in weight is expected for the intermediate spars, the weight savings produced by the upper cover will adequately compensate for it and yield an overall weight savings.

The same loading conditions, that sized our previous spar concepts, were used to size the Y-spar configuration. For all Y-spar designs, the angle was set at 120° to provide equilibrium and balance. The distance between the legs of the Y-spar at the attachment to the upper cover depends on the spar spacing. To obtain the maximum benefit from the Y-spar configuration, the fasteners should be located so as to divide the spar spacing in half. Using results from BL25 as an example, this is shown in Fig. 22. Knowing the fastener distance of 4.6 in., we can obtain the 3.4-in. spacing by accounting for the proper edge distance for the fasteners. Once the general dimensions of the Y-spars were known, sizing of their legs and web was accomplished.

2.5.2 Multi-Rib: Y-Stiffened

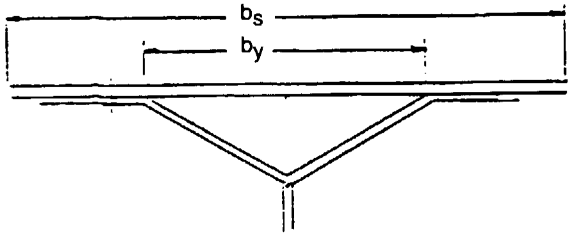
An approach similar to that of the previous stiffened configurations was undertaken using "Y" stiffeners. An integrally molded structure, using G40-800/F584, was designed to achieve high strain capability. However, the lower cover differed from the upper cover with a spread 0° design supported by blade stiffeners. The same rib concept (Gr/Ep stiffeners and angles mechanically attached) and front/rear spars (angle-stiffened) were utilized as in previous multi-rib configurations.

2.6 WEIGHT ANALYSIS

2.6.1 Material – Oriented Concepts

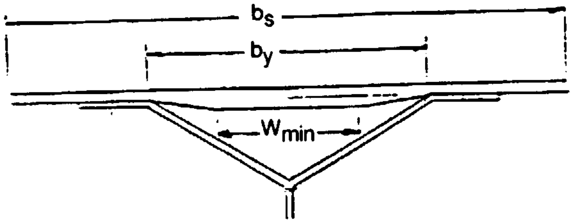
For the baseline wing and the various high-strain wing concepts, theoretical cover and substructure weights were derived analytically on a multi-station-wise basis utilizing t's generated for the various forms of construction. To account for such weight items as penalties associated with load introduction, attachments, cutouts, and variations in laminate thickness and density, the theoretical weights were multiplied by an empirically determined "non-optimum factor", thereby yielding a realistic assembly weight. The results of the multi-spar and multi-rib concepts studied are shown in Tables 9, 10, and 11.

- SPREAD 0° SUPPORTED BY Y-SPARS



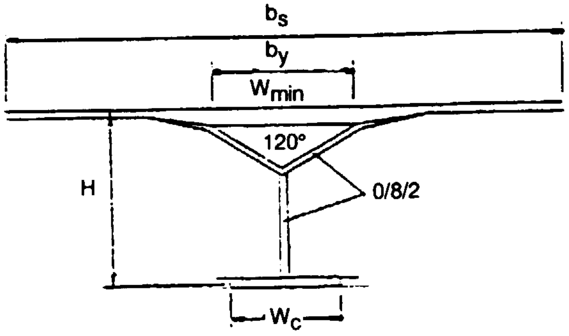
		b_s, in.	b_y, in.	LAMINATE 0/±45/90	$\bar{t}$, in.
BL 25	5-SPAR	9.20	3.40	16/16/4	0.1886
	6-SPAR	7.40	3.00	16/12/4	0.1677
BL 150	5-SPAR	6.50	2.60	8/12/2	0.1153
	6-SPAR	5.00	2.00	8/8/2	0.0943
BL 200	5-SPAR	5.00	1.90	4/8/2	0.0734
	6-SPAR	3.80	1.40	4/6/2	0.0629

- ISOLATED DISCRETE CAP SUPPORTED BY Y-SPARS



		b_s, in.	b_y, in.	Wmin in.	PAD 0/±45/90	SKIN 0/±45/90	$\bar{t}$, in.
BL 25	5-SP	9.20	4.75	2.83	32/22/6	9/22/6	0.2158
	6-SP	7.40	4.23	2.43	30/20/6	0/20/6	0.2070
BL 150	5-SP	6.50	2.54	1.34	20/14/4	0/14/4	0.1256
	6-SP	5.00	2.28	1.20	18/12/4	0/12/4	0.1167
BL 200	5-SP	5.00	2.32	1.96	6/8/2	0/8/2	0.0659
	6-SP	3.80	1.76	1.40	6/8/2	0/8/2	0.0655

- ISOLATED DISCRETE CAP SUPPORTED BY Y-STIFFENERS



		b_s, in.	b_y, & Wmin, in.	W_c in.	h, in.	PAD 0/±45/90	CAP 0/±45/90	$\bar{t}$, in.
BL 25	4-SP	11.5	3.64	1.10	3.50	34/22/6	6/8/2	0.2558
BL 150	5-SP	6.50	1.50	1.34	1.50	20/14/4	6/8/2	0.1664
BL 200	5-SP	5.00	2.15	0.70	1.50	6/8/2	4/8/2	0.0883

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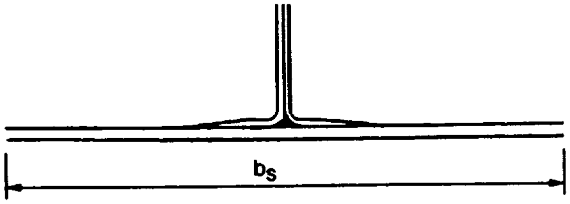
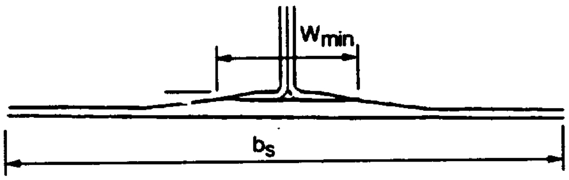
Fig. 20 Summary of Upper Cover Sizing

- SPREAD 0° SUPPORTED BY Y-SPARS



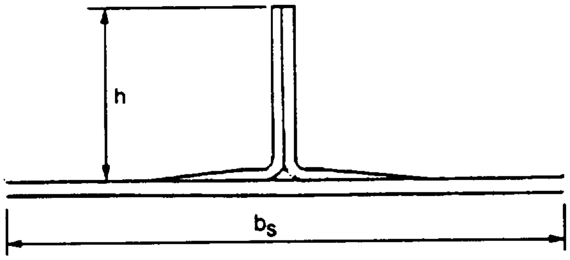
		b_s, in.	LAMINATE 0/±45/90	$\bar{t}$, in.
BL 25	5-SPAR	9.20	12/26/4	0.2201
	6-SPAR	7.40	12/20/4	0.1886
BL 150	5-SPAR	6.50	6/16/4	0.1362
	6-SPAR	5.00	6/14/2	0.1153
BL 200	5-SPAR	5.00	3/12/2	0.0891
	6-SPAR	3.80	4/8/2	0.0734

- DISCRETE CAP SUPPORTED BY Y-SPARS



		b_s, in.	W_{min} in.	LAMINATE 0/±45/90	$\bar{t}$, in.
BL 25	5-SP	9.20	1.93	36/22/4	0.1979
	6-SP	7.40	1.45	36/18/4	0.1798
BL 50	5-SP	6.50	0.97	24/14/4	0.1270
	6-SP	5.00	1.08	18/12/2	0.1040
BL 200	5-SP	5.00	0.99	12/10/2	0.0799
	6-SP	3.80	1.52	6/8/2	0.0665

- SPREAD 0° SUPPORTED BY BLADE STIFFENERS



		b_s, in.	h, in.	SKIN 0/±45/90	BLADE 0/±45/90	$\bar{t}$, in.
BL 25	4-STFS	9.20	1.85	8/26/4	18/204	0.2434
	5	7.40	1.85	8/20/4	16/20/4	0.2201
	6	6.57	1.80	8/18/2	16/20/4	0.2041
BL 150	6-STFS	3.71	1.60	4/10/2	2/16/4	0.1335
	5	4.33	1.70	4/12/2	2/16/4	0.1396
	4	5.20	1.60	4/14/2	5/16/4	0.1451
BL 200	5-STFS	3.25	1.50	2/8/2	0/12/4	0.1016
	4	3.90	1.60	2/10/2	0/12/4	0.1078
	3	4.88	1.70	2/12/2	0/12/4	0.1130

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Fig. 21 Summary of Lower Cover Sizing

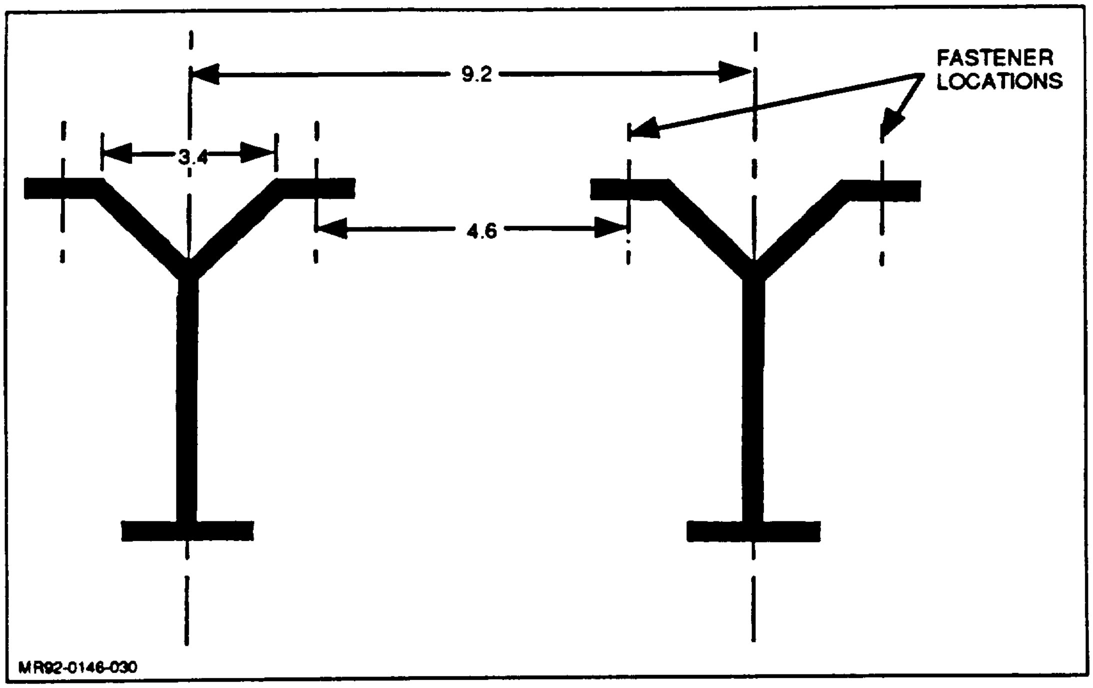

Fig. 22 Y-Spar Configuration

Table 12 shows a weight breakdown of the multi-spar design, for both material systems (IM7/8551-7A and G40-800/F584 Gr/Ep), and multi-rib design (IM7/Tactix 123 Gr/Ep). The multi-rib design concept, shown in Fig. 23, consists of four hat stiffeners outboard of the fold, seven inboard, and twenty-five ribs at a 25-in. pitch. A combination of factors (weights, manufacturing and production costs, durability, repairability, etc) will determine the ultimate selection. The weight savings generated by these concepts show significant improvement over the baseline. The multi-spar design, using G40-800/F584, provided a savings of 543 lb or 42% of the metal torque box weight of 1233 lb. The multi-rib design, using IM7/Tactix 123 Gr/Ep, yielded a 541-lb savings or 41% of the metal torque box weight.

2.6.2 Combined Material/Configuration Concepts

Similar to previous material-oriented design concepts, the theoretical weights, derived for the material/configuration concepts were multiplied by an empirically determined "non-optimum factor" to yield a realistic assembly weight. Table 13 shows a weight breakdown of the multi-spar designs (spread 0° and discrete cap) and multi-rib design. The weight savings generated by these concepts show significant improvement over the baseline. The multi-rib design, using G40-800/F584 with "Y" stiffeners, provided the greatest savings with 573 lb or 46% of the metal torque box weight of 1233 lb. A combination of factors (weights, manufacturing and production costs, durability, repairability, etc) will determine the final selection between these material/configurations concepts and the material-oriented concepts previously described.

TABLE 9 WEIGHT SUMMARY, UNBUCKLED AND BUCKLED INTEGRAL HAT MULTI-RIB CONCEPTS, lb

	BASIC COVERS		FRONT & REAR SPARS		RIBS	TOTAL BOX	
	TENSION	COMPRESSION	UNSTIFF.	ANGLE-STIFF.		UNSTIFF. SPARS	ANGLE-STIFF. SPARS
HAT STIFFENED – UNBUCKLED							
RIB SPACING, (15 in.), STRING SPACE (4 in.)	170.70	204.70	147.20	138.90	111.70	634.30	626.00
RIB SPACING, (15 in.), STRING SPACE (5 in.)	177.80	217.40	147.20	138.90	114.00	656.40	648.10
RIB SPACING, (15 in.), STRING SPACE (6 in.)	187.50	238.90	147.20	138.90	112.80	686.40	678.10
RIB SPACING, (15 in.), STRING SPACE (7 in.)	201.00	249.00	147.20	138.90	112.90	710.10	701.80
RIB SPACING, (20 in.), STRING SPACE (4 in.)	175.70	227.90	147.20	138.90	114.60	665.40	657.10
RIB SPACING, (20 in.), STRING SPACE (5 in.)	181.80	238.60	147.20	138.90	103.20	670.80	662.50
RIB SPACING, (20 in.), STRING SPACE (6 in.)	189.80	256.60	147.20	138.90	112.90	706.50	698.20
RIB SPACING, (20 in.), STRING SPACE (7 in.)	208.00	278.60	147.20	138.90	107.70	741.50	733.20
RIB SPACING, (25 in.), STRING SPACE (4 in.)	180.90	243.30	147.20	138.90	97.80	669.20	660.90
RIB SPACING, (25 in.), STRING SPACE (5 in.)	187.00	259.80	147.20	138.90	102.80	696.80	688.50
RIB SPACING, (25 in.), STRING SPACE (6 in.)	195.50	280.60	147.20	138.90	96.60	719.90	711.60
RIB SPACING, (25 in.), STRING SPACE (7 in.)	204.80	297.00	147.20	138.90	103.90	752.90	744.60
RIB SPACING, (30 in.), STRING SPACE (4 in.)	187.00	264.90	147.20	138.90	96.60	695.70	687.40
RIB SPACING, (30 in.), STRING SPACE (5 in.)	192.40	280.80	147.20	138.90	104.90	725.30	717.00
RIB SPACING, (30 in.), STRING SPACE (6 in.)	200.30	298.90	147.20	138.90	105.80	752.20	743.90
RIB SPACING, (30 in.), STRING SPACE (7 in.)	210.40	319.90	147.20	138.90	104.20	781.70	773.40
HAT STIFFENED – BUCKLED							
RIB SPACING, (15 in.), STRING SPACE (4 in.)	162.20	194.50	147.20	138.90	111.70	615.60	607.30
RIB SPACING, (15 in.), STRING SPACE (5 in.)	168.90	206.50	147.20	138.90	114.00	636.60	628.30
RIB SPACING, (15 in.), STRING SPACE (6 in.)	178.10	227.00	147.20	138.90	112.80	665.10	656.80
RIB SPACING, (15 in.), STRING SPACE (7 in.)	191.00	236.60	147.20	138.90	112.90	687.70	679.40
RIB SPACING, (20 in.), STRING SPACE (4 in.)	166.90	211.80	147.20	138.90	114.60	640.50	632.20
RIB SPACING, (20 in.), STRING SPACE (5 in.)	172.70	226.70	147.20	138.90	103.20	649.80	641.50
RIB SPACING, (20 in.), STRING SPACE (6 in.)	180.30	243.80	147.20	138.90	112.90	684.20	675.90
RIB SPACING, (20 in.), STRING SPACE (7 in.)	197.60	264.70	147.20	138.90	107.70	717.20	708.90
RIB SPACING, (25 in.), STRING SPACE (4 in.)	244.20	231.10	147.20	138.90	97.80	720.30	712.00
RIB SPACING, (25 in.), STRING SPACE (5 in.)	177.70	246.20	147.20	138.90	102.80	673.90	665.60
RIB SPACING, (25 in.), STRING SPACE (6 in.)	185.70	266.60	147.20	138.90	96.60	696.10	687.80
RIB SPACING, (25 in.), STRING SPACE (7 in.)	194.60	282.20	147.20	138.90	103.90	727.90	719.60
RIB SPACING, (30 in.), STRING SPACE (4 in.)	177.70	251.70	147.20	138.90	96.60	673.20	664.90
RIB SPACING, (30 in.), STRING SPACE (5 in.)	182.80	266.80	147.20	138.90	104.90	701.70	693.40
RIB SPACING, (30 in.), STRING SPACE (6 in.)	190.30	284.00	147.20	138.90	105.80	727.30	719.00
RIB SPACING, (30 in.), STRING SPACE (7 in.)	200.00	303.90	147.20	138.90	104.20	755.30	747.00

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TABLE 10 WEIGHT SUMMARY, UNBUCKLED AND BUCKLED INTEGRAL J – STIFFENED MULTI-RIB CONCEPTS, lb

	BASIC COVERS		FRONT & REAR SPARS		RIBS	TOTAL BOX	
	TENSION	COMPRESSION	UNSTIFF.	ANGLE-STIFF		UNSTIFF. SPARS	ANGLE-STIFF. SPARS
J-STIFFENED – UNBUCKLED							
RIB SPACING, (15 in.), STIFF SPACE (4 in.)	249.40	276.10	147.20	138.50	111.70	784.40	775.70
RIB SPACING, (15 in.), STIFF SPACE (5 in.)	257.80	288.20	147.20	138.50	114.00	807.20	798.50
RIB SPACING, (15 in.), STIFF SPACE (6 in.)	278.30	299.60	147.20	138.50	112.80	837.90	829.20
RIB SPACING, (15 in.), STIFF SPACE (7 in.)	288.80	311.80	147.20	138.50	112.90	860.70	852.00
RIB SPACING, (20 in.), STIFF SPACE (4 in.)	240.40	280.50	147.20	138.50	114.60	782.70	774.00
RIB SPACING, (20 in.), STIFF SPACE (5 in.)	248.40	296.10	147.20	138.50	103.20	794.90	786.20
RIB SPACING, (20 in.), STIFF SPACE (6 in.)	261.90	307.10	147.20	138.50	112.90	829.10	820.40
RIB SPACING, (20 in.), STIFF SPACE (7 in.)	270.90	327.20	147.20	138.50	107.70	853.00	844.30
RIB SPACING, (25 in.), STIFF SPACE (4 in.)	247.20	289.70	147.20	138.50	97.80	781.90	773.20
RIB SPACING, (25 in.), STIFF SPACE (5 in.)	257.10	302.40	147.20	138.50	102.80	809.50	800.80
RIB SPACING, (25 in.), STIFF SPACE (6 in.)	267.00	320.60	147.20	138.50	96.60	831.40	822.70
RIB SPACING, (25 in.), STIFF SPACE (7 in.)	277.60	332.80	147.20	138.50	103.90	861.50	852.80
RIB SPACING, (30 in.), STIFF SPACE (4 in.)	249.30	303.40	147.20	138.50	96.60	796.50	787.80
RIB SPACING, (30 in.), STIFF SPACE (5 in.)	261.00	317.00	147.20	138.50	104.90	830.10	821.40
RIB SPACING, (30 in.), STIFF SPACE (6 in.)	273.00	330.30	147.20	138.50	105.80	856.30	847.60
RIB SPACING, (30 in.), STIFF SPACE (7 in.)	284.00	351.40	147.20	138.50	104.20	886.80	878.10
J-STIFFENED – BUCKLED							
RIB SPACING, (15 in.), STIFF SPACE (4 in.)	236.90	262.30	147.20	138.90	111.70	758.10	749.80
RIB SPACING, (15 in.), STIFF SPACE (5 in.)	246.80	273.80	147.20	138.90	114.00	781.80	773.50
RIB SPACING, (15 in.), STIFF SPACE (6 in.)	264.40	284.60	147.20	138.90	112.80	809.00	800.70
RIB SPACING, (15 in.), STIFF SPACE (7 in.)	274.40	296.20	147.20	138.90	112.90	830.70	822.40
RIB SPACING, (20 in.), STIFF SPACE (4 in.)	228.40	266.50	147.20	138.90	114.60	756.70	748.40
RIB SPACING, (20 in.), STIFF SPACE (5 in.)	236.00	281.30	147.20	138.90	103.60	768.10	759.80
RIB SPACING, (20 in.), STIFF SPACE (6 in.)	248.80	291.70	147.20	138.90	112.60	800.30	792.00
RIB SPACING, (20 in.), STIFF SPACE (7 in.)	257.40	310.80	147.20	138.90	107.70	823.10	814.80
RIB SPACING, (25 in.), STIFF SPACE (4 in.)	234.80	275.20	147.20	138.90	97.80	755.00	746.70
RIB SPACING, (25 in.), STIFF SPACE (5 in.)	244.20	287.30	147.20	138.90	102.80	781.50	773.20
RIB SPACING, (25 in.), STIFF SPACE (6 in.)	253.70	304.60	147.20	138.90	96.60	802.10	793.80
RIB SPACING, (25 in.), STIFF SPACE (7 in.)	263.70	316.20	147.20	138.90	103.90	831.00	822.70
RIB SPACING, (30 in.), STIFF SPACE (4 in.)	236.80	288.20	147.20	138.90	96.60	768.80	760.50
RIB SPACING, (30 in.), STIFF SPACE (5 in.)	248.20	301.20	147.20	138.90	104.90	801.50	793.20
RIB SPACING, (30 in.), STIFF SPACE (6 in.)	259.40	313.80	147.20	138.90	105.80	826.20	817.90
RIB SPACING, (30 in.), STIFF SPACE (7 in.)	269.80	333.30	147.20	138.90	104.20	854.50	846.20

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TABLE 11 SUMMARY OF MULTI-SPAR COMPONENT WEIGHTS

COVER CONFIGURATION	MATERIAL	TOTAL COVER WEIGHT, lb
COMPRESSION		
PLAIN PANEL	IM7/8551-7A	310.60
PLAIN PANEL	G40-800/F584	306.20
DISCRETE CAP	IM7/8551-7A	257.00
DISCRETE CAP	G40-800/F584	247.50
DISCRETE CAP/BUCK @ LL	IM7/8551-7A	223.90
DISCRETE CAP/BUCK @ LL	G40-800/F584	211.80
TENSION		
PLAIN PANEL	IM7/8551-7A	244.50
PLAIN PANEL	G40-800/F584	239.40
DISCRETE CAP	IM7/8551-7A	201.20
DISCRETE CAP	G40-800/F584	193.60
DISCRETE CAP/BUCK @ LL	IM7/8551-7A	175.30
DISCRETE CAP/BUCK @ LL	G40-800/F584	165.60

SPAR CONFIGURATION *	FRONT SPAR, lb	REAR SPAR, lb	INTER. SPAR, lb
PLAIN PANEL	52.3	43.6	132.4
ANGLE STIFFENED	44.3	37.5	110
SYNCORE STIFFENED	36.9	32.9	101.8
SINEWAVE	42.9	28.6	80.1
*WEB WEIGHTS ONLY			

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TABLE 12 WEIGHT BREAKDOWN FOR SELECTED WING DESIGNS (MATERIAL-ORIENTED CONCEPTS)

COMPONENT	BASELINE WING TORQUE BOX, lb	MULTI-SPAR IM7/8551-7A, lb	MULTI-SPAR G40-800/F584, lb	MULTI-RIB (CONCEPT C) HAT-STIFFENED
UPPER COVER	293.80	258.30	246.20	266.60
• BASIC INTERSPAR COVER	240.50	223.90	211.80	266.60
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.60	—	—	—
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	10.60	—	—	—
• DAMAGE TOLERANCE PENALTY (+45° Gl/Ep	0.00	—	—	—
• SPAR CAPS (INC. WRINKLING PENALTY)	40.10	34.40	34.40	—
LOWER COVER	224.10	192.40	182.70	185.70
• BASIC INTERSPAR COVER	187.20	175.30	165.60	185.70
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.20	—	—	—
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	8.00	—	—	—
• DAMAGE TOLERANCE PENALTY (+45° Gl/Ep	1.50	—	—	—
• SPAR CAPS (INC WRINKLING PENALTY)	24.90	17.10	17.10	—
FRONT SPAR (SYNCORE STIFF)	88.60	73.80	73.80	98.80
REAR SPAR (SYNCORE STIFF)	36.00	32.90	32.90	40.10
INTERMEDIATE SPARS (SYNCORE STIFF)	110.00	101.80	101.80	—
RIBS	52.20	52.20	52.20	96.60
TOTAL TORQUE BOX	806.20	711.40	689.60	687.80
WEIGHT SAVINGS OVER BASELINE	—	94.80	116.60	118.40
% SAVINGS	—	11.80	14.50	14.70

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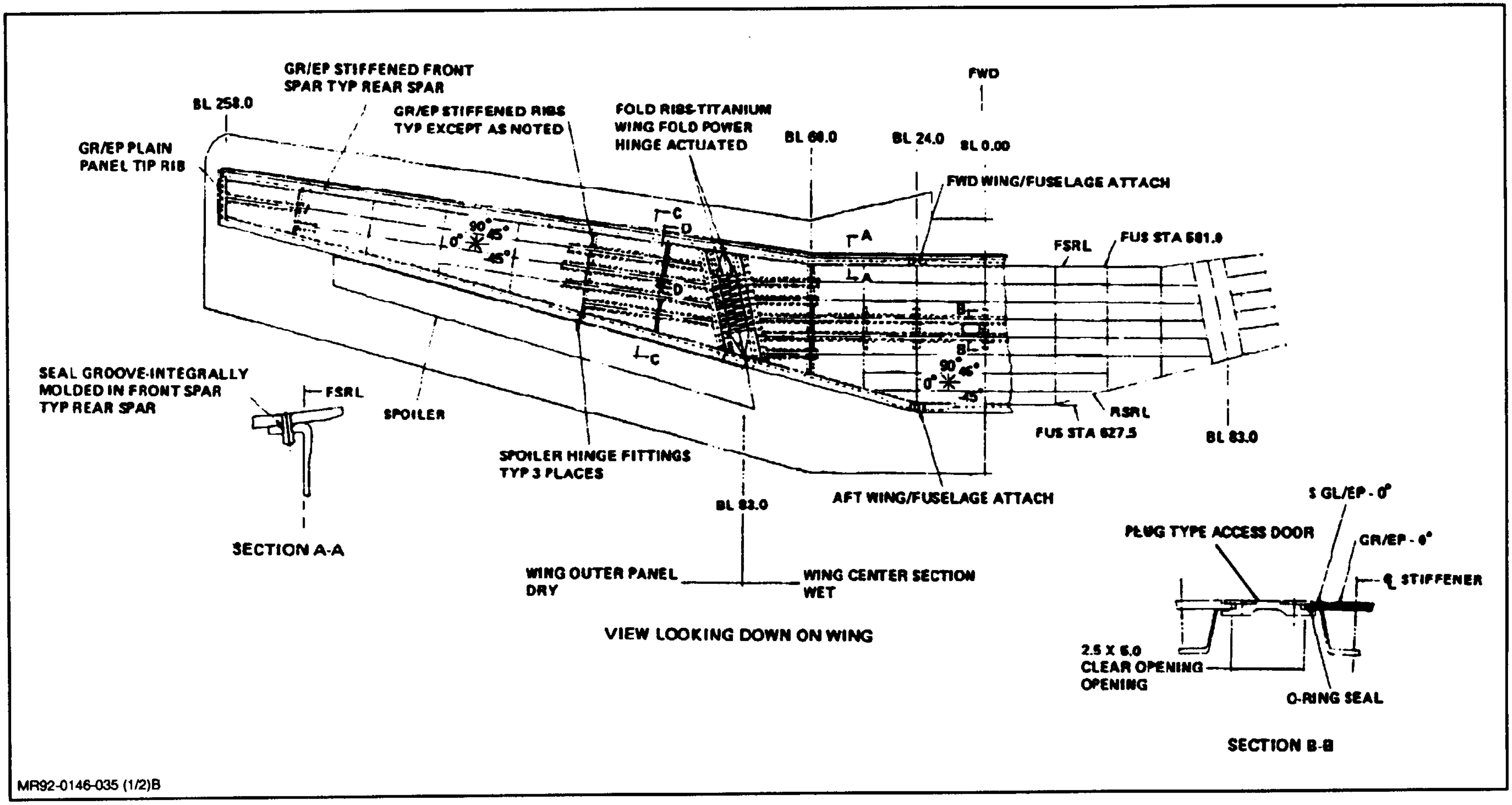

Fig. 23 Multi-Rib Design (Sheet 1 of 2)

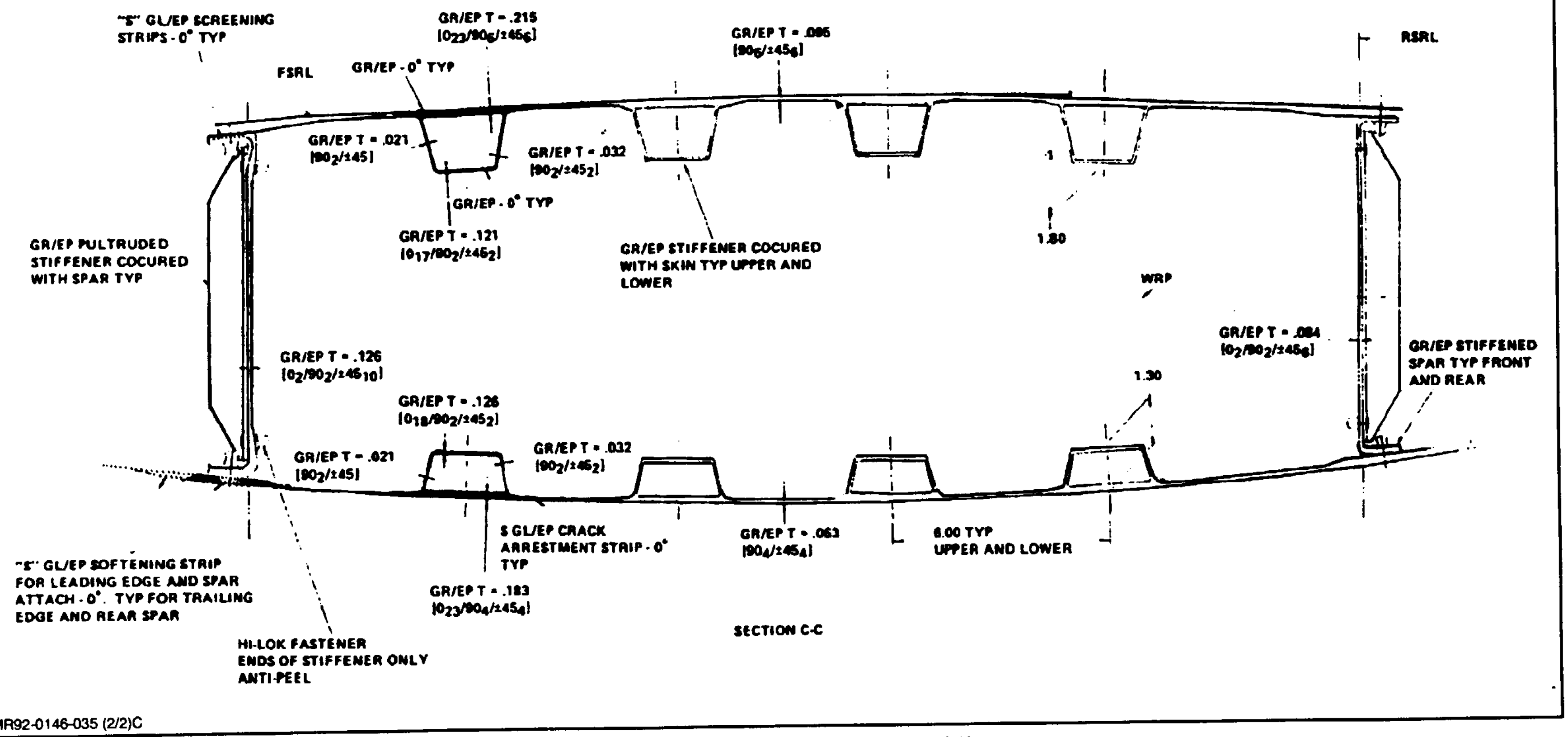

Fig. 23 Multi-Rib Design (Sheet 2 of 2)

TABLE 13 WEIGHT BREAKDOWN FOR SELECTED WING DESIGNS (MATERIAL AND CONFIGURATION)

COMPONENT	BASELINE WING TORQUE BOX, lb	MULTI-SPAR (SPREAD 0°)	MULTI-SPAR (DISCRETE CAP)	MULTI-RIB (Y-STIFFENED)
UPPER COVER	293.80	182.80	191.50	215.50
• BASIC INTERSPAR COVER	240.50	169.00	177.70	215.50
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.60	—	—	—
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	10.60	—	—	—
• DAMAGE TOLERANCE PENALTY (±45° Gl/Ep)	0.00	—	—	—
• SPAR CAPS (INCL WRINKLING PENALTY)	40.10	13.80	13.80	—
LOWER COVER	224.10	207.00	186.60	208.90
• BASIC INTERSPAR COVER	187.20	200.20	179.80	208.90
• SOFTENING STRIP PENALTY (0° Gl/Ep)	2.20	—	—	—
• DAMAGE TOLERANCE PENALTY (0° Gl/Ep)	8.00	—	—	—
• DAMAGE TOLERANCE PENALTY (±45° Gl/Ep)	1.50	—	—	—
• SPAR CAPS (INCL WRINKLING PENALTY)	24.90	6.80	6.80	—
FRONT SPAR (SYNCORE STIFFENED)	88.60	73.80	73.80	98.80
REAR SPAR (SYNCORE STIFFENED)	36.00	32.90	32.90	40.10
INTERMEDIATE SPARS (Y-SPARS)	110.00	159.00	159.00	—
RIBS	52.20	52.20	52.20	96.60
TOTAL TORQUE BOX	806.20	707.70	696.00	659.90
WEIGHT SAVINGS OVER BASELINE	—	98.50	110.20	146.30
% SAVINGS	—	12.20	13.70	18.10

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2.7 COST ANALYSIS

Cost estimating of the baseline high-strain wing and the novel composites wing concepts was performed. The Grumman-modified advanced composite cost estimating model "FACET" was used to generate estimates for detail part fabrication and assembly costs. "FACET" includes factory labor standard estimating and cost projections, and utilizes industrial engineering time standards to calculate pure labor hours associated with detail fabrication operations performed. When operations occur that are not covered by the "FACET" capability, a detailed estimating process is employed. Both methods are based on Grumman historical cost data and industrial engineering time standards; therefore, they are consistent and compatible. To account for other elements involved in production (i.e., learning curves, delays, fatigue, etc), variable factors are applied to these standards in the cost projections portion of the model. These estimates reflect only recurring costs, which are those hours incurred in direct production and delivery of each part on a sustaining and repetitive basis. These hours include factory labor for direct manufacturing operations, such as material dispensing, setup time, automatic layup, ply cutting and handling, processing, bonding, autoclave and oven curing, and final assembly. Also, included are costs for supporting functional groups such as sustaining engineering, tool maintenance, quality control, and manufacturing engineering. Nonrecurring costs were not included in the average unit values because they are usually one-time costs and are not incurred during the production of each detail. A labor rate of $50/hr was assumed in the cost analysis.

Tables 14 through 20 and Tables 21 through 27 show the cost summary of the first unit (prototype) and the hundredth unit, respectively, for the baseline and the novel composites wing concepts. These tables exclude estimates for the titanium fold ribs as well as the root and tip ribs, since they are identical for all the concepts and would not affect cost comparisons.

**TABLE 14 RECURRING COST SUMMARY:
FIRST UNIT - BASELINE
(HIGH-STRAIN WING), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	29.4	18.3	47.7
LOWER COVER	24.5	14.3	38.8
FRONT SPAR	22.2	7.6	29.8
INTERMEDIATE SPARS	30.5	10.9	41.4
REAR SPAR	13.7	3.6	17.3
RIBS	12.8	2.9	15.7
ASSEMBLY	35.4	6.3	41.7
TOTAL	168.5	63.9	232.4

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**TABLE 15 RECURRING COST SUMMARY:
FIRST UNIT – CONCEPT I (MULTI-SPAR), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	27.0	32.2	59.2
LOWER COVER	22.8	25.2	48.0
FRONT SPAR	15.0	10.4	25.4
INTERMEDIATE SPARS	22.8	14.3	37.1
REAR SPAR	10.1	4.4	14.5
RIBS	12.3	5.3	17.6
ASSEMBLY	35.4	6.3	41.7
TOTAL	145.4	98.1	243.5

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TABLE 16 RECURRING COST SUMMARY:
FIRST UNIT - CONCEPT II
(MULTI-SPAR), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	25.5	30.5	56.0
LOWER COVER	21.8	23.8	45.6
FRONT SPAR	15.0	10.4	25.4
INTERMEDIATE SPARS	22.8	14.3	37.1
REAR SPAR	10.1	4.4	14.5
RIBS	12.3	5.3	17.6
ASSEMBLY	35.4	6.3	41.7
TOTAL	142.9	95.0	237.9

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TABLE 17 RECURRING COST SUMMARY:
FIRST UNIT – CONCEPT III (MULTI-RIB), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	19.9	34.6	54.5
LOWER COVER	16.9	24.1	41.0
FRONT SPAR	14.3	12.8	27.1
INTERMEDIATE SPARS	–	–	–
REAR SPAR	8.9	5.2	14.1
RIBS	21.0	12.5	33.5
ASSEMBLY	24.7	3.5	28.2
TOTAL	105.7	92.7	198.4

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TABLE 18 RECURRING COST SUMMARY:
FIRST UNIT – CONCEPT IV (MULTI-SPAR), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	21.5	24.4	45.9
LOWER COVER	25.4	28.8	54.2
FRONT SPAR	14.3	9.5	23.8
INTERMEDIATE SPARS	19.3	20.6	39.9
REAR SPAR	8.9	4.1	13.0
RIBS	12.3	5.3	17.6
ASSEMBLY	40.1	8.4	48.5
TOTAL	141.8	101.1	242.9

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TABLE 19 RECURRING COST SUMMARY:
FIRST UNIT – CONCEPT V (MULTI-SPAR), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	22.5	25.7	48.2
LOWER COVER	22.8	25.9	48.7
FRONT SPAR	14.3	9.5	23.8
INTERMEDIATE SPARS	19.3	20.6	39.9
REAR SPAR	8.9	4.1	13.0
RIBS	12.3	5.3	17.6
ASSEMBLY	40.1	8.4	48.5
TOTAL	140.2	99.5	239.7

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**TABLE 20 RECURRING COST SUMMARY:
FIRST UNIT – CONCEPT VI (MULTI-RIB), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	19.4	28.0	47.4
LOWER COVER	16.4	27.1	43.5
FRONT SPAR	14.3	12.8	27.1
INTERMEDIATE SPARS	–	–	–
REAR SPAR	8.9	5.2	14.1
RIBS	21.0	12.5	33.5
ASSEMBLY	24.7	3.5	28.2
TOTAL	104.7	89.1	193.8

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**TABLE 21 RECURRING COST SUMMARY:
100th UNIT – BASELINE (HIGH-STRAIN WING), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	13.2	15.2	28.4
LOWER COVER	10.8	11.8	22.6
FRONT SPAR	9.2	6.2	15.4
INTERMEDIATE SPARS	11.1	9.0	20.1
REAR SPAR	5.7	3.0	8.7
RIBS	4.8	2.4	7.2
ASSEMBLY	12.2	5.7	17.9
TOTAL	67.0	53.3	120.3

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**TABLE 22 RECURRING COST SUMMARY:
100th UNIT – CONCEPT I (MULTI-SPAR), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	8.3	26.8	35.1
LOWER COVER	6.9	20.9	27.8
FRONT SPAR	4.9	8.6	13.5
INTERMEDIATE SPARS	7.4	11.8	19.2
REAR SPAR	3.2	3.7	6.9
RIBS	4.7	4.4	9.1
ASSEMBLY	12.2	5.7	17.9
TOTAL	47.6	81.9	129.5

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**TABLE 23 RECURRING COST SUMMARY:
100th UNIT – CONCEPT II (MULTI-SPAR), $K**

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	7.8	25.3	33.1
LOWER COVER	6.6	19.8	26.4
FRONT SPAR	4.9	8.6	13.5
INTERMEDIATE SPARS	7.4	11.8	19.2
REAR SPAR	3.2	3.7	6.9
RIBS	4.7	4.4	9.1
ASSEMBLY	12.2	5.7	17.9
TOTAL	46.8	79.3	126.1

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TABLE 24 RECURRING COST SUMMARY:
100th UNIT – CONCEPT III (MULTI-RIB), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	5.9	28.8	34.7
LOWER COVER	5.0	20.0	25.0
FRONT SPAR	4.6	10.7	15.3
INTERMEDIATE SPARS	–	–	–
REAR SPAR	2.8	4.3	7.1
RIBS	6.6	10.4	17.0
ASSEMBLY	8.5	3.2	11.7
TOTAL	33.4	77.4	110.8
MR92-0146-047			

TABLE 25 RECURRING COST SUMMARY:
100th UNIT – CONCEPT IV (MULTI-SPAR), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	6.4	20.2	26.6
LOWER COVER	7.8	23.9	31.7
FRONT SPAR	4.6	7.8	12.4
INTERMEDIATE SPARS	6.3	17.1	23.4
REAR SPAR	2.8	3.3	6.1
RIBS	4.7	4.4	9.1
ASSEMBLY	13.2	7.7	20.9
TOTAL	45.8	84.4	130.2
MR92-0146-048			

TABLE 26 RECURRING COST SUMMARY: 100th UNIT – CONCEPT V (MULTI-SPAR), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	7.4	21.3	28.7
LOWER COVER	6.9	21.5	28.4
FRONT SPAR	4.6	7.8	12.4
INTERMEDIATE SPARS	6.3	17.1	23.4
REAR SPAR	2.8	3.3	6.1
RIBS	4.7	4.4	9.1
ASSEMBLY	13.2	7.7	20.9
TOTAL	45.9	83.1	129.0
MR92-0146-049			

TABLE 27 RECURRING COST SUMMARY: 100th UNIT – CONCEPT VI (MULTI-RIB), $K

COMPONENT	LABOR	MATERIAL	TOTAL
UPPER COVER	5.7	23.2	28.9
LOWER COVER	4.8	22.5	27.3
FRONT SPAR	4.6	10.7	15.3
INTERMEDIATE SPARS	–	–	–
REAR SPAR	2.8	4.3	7.1
RIBS	6.6	10.4	17.0
ASSEMBLY	8.5	3.2	11.7
TOTAL	33.0	74.3	107.3
MR92-0146-050			

For the first unit (prototype) and hundredth unit, Concepts III and VI provide significant savings over the baseline in each case. Concept VI (Multi-Rib, Y-stiffened) has the greatest savings at approximately 16.5% ($38,600) and 11% ($13,000) for the first and hundredth units, respectively. Although the remaining concepts were higher in cost, one must realize this is due to the significant price difference of the Gr/Ep material used. For the baseline, the Gr/Ep cost is $40/lb compared to $80/lb for the innovative materials used for the other concepts. However, as expected with new material systems, their costs tend to decline with time and increased usage by the industry. Therefore, all concepts developed will eventually match or save money over the baseline cost and can be considered for possible future application.

2.8 CONCEPT SELECTION

2.8.1 Rating Analysis

After the trade studies were completed, a rating analysis was conducted. Table 28 illustrates the procedure used in rating the wing box concepts. Each design concept was rated in terms of the following parameters: weight, risk, manufacturing and production costs, durability/damage tolerance, repairability, inspectability, and operation and support costs:

- Weight – Rating is straightforward, with the lightest concept getting the highest rating and the heaviest the lowest rating
- Risk – Defined as the concepts' inability to meet program objectives (concept with the highest risk receives the lowest rating)
- Manufacturing and Production Costs – The following manufacturing tasks are reflected in the cost data developed for the wing:
  - Manufacturing Manhours – Fabrication of structural details and assemblies for delivery of 500 units
  - Manufacturing Supporting Services – Level of effort function for both RDT&E and production that includes such items as industrial engineering, production control, scheduling and business office
  - Quality Control – This effort is for both RDT&E and production and includes inspection of vehicle structure and tools
  - Tool Design – The functional departments within Tool Design have the responsibility to design all tooling. During the RDT&E phase, a basic tooling package is designed. During the production phase, Tool Design is responsible for rate tooling and recurring tooling
  - Methods – Methods Engineering is responsible for the planning and ordering of all tooling, including non-designed tools
  - Tool Fabrication – All tool fabrication and repair in RDT&E and production are handled by Tool Fabrication

TABLE 28 RATING ANALYSIS

ITEM	FACTOR	RATING	SCORE
WEIGHT	25		
RISK	10		
MFG COSTS (RDT&E & PRODUCTION	18		
OPS & SPT COSTS	8		
DURABILITY & SURVIVABILITY	14		
REPAIRABILITY	15		
INSPECTABILITY/ACCESS	10		
MR92-0146-051			
RATINGS 1 THRU 10: 1 – POOR 10 – EXCELLENT HIGH SCORE WINS			

- Durability/Survivability – The durability of the structures were evaluated with respect to minimizing stress concentrations, notches, abrupt area changes, peel-prone joints, etc, and with respect to ease of fabricating defect-free parts so as to eliminate, from the outset, sources of microcracks or delamination
- Repairability – A measure of the ability to restore the functional and structural capability of the damage component by positive but simple repair methods was used as a criteria for repairability. The types of damage which occur during fabrication and service have been identified and categorized for various types of composite structures. A basis for rating the repairability of the advanced composite design concepts was provided by past experience
- Inspection/Access – Availability of access panels and the ability to provide inspection holes and relative clutter was considered. Large, open volumes are easiest to inspect. After determining the need for access for the purpose of service and maintenance, the different concepts were rated for the amount of access provided, and the penalties of providing the access in terms of weight, interruption of load paths, sealing problems, etc
- Operations and Support Costs – These ratings were based on estimates of relative costs of deploying and maintaining an aircraft with the configuration being examined. Included are estimates of costs associated with maintainability, accessibility, reliability, and repairability.

The rating parameters were assigned a weighting factor in accordance with perceived relative importance. Each concept was rated with respect to each other by a rating factor from 1 to 10. The final score was obtained by summing the product of the weighting factor times the rating. A higher final score indicates a better balanced design.

2.8.2 Evaluation

With the concept rating forms, along with layouts, engineers from different disciplines were able to rate the various novel composites wing concepts. These disciplines included Advanced Materials and Manufacturing, Tooling, Design, Structural Analysis, Quality Control, and Reliability/Maintainability. The results are incorporated in Tables 29 and 30, for the multi-spar and multi-rib concepts, respectively. The Total Score column represents the total of each discipline score for that parameter. The Average Score column represents the Total Score divided by the No. of R (rating disciplines), which is four (4) in all cases. For example, for the first parameter, Weight, Concept I received scores of 100, 125, 125, and 100 from the four disciplines, which resulted in a Total Score of 450 and an Average Score of 113 (450/4). The sum of the Average Scores then represent the rating for that particular concept.

To obtain useful information and conclusions from these tables, one must realize that the design concepts encompass different stages of development. This would tend to favor concepts where proven design and manufacturing processes are utilized. Therefore, three classifications of development were devised, with each concept assigned to one of the following:

1. State-of-the-Art – Represents concepts that utilize current or proven design techniques and manufacturing processes. Innovative material approach without 3-D weave or innovative manufacturing processes
2. In-Development – Represents concepts that utilize innovative designs, such as the Y-spar configuration, and innovative manufacturing processes (RTM, RFI, Autocomp, Consolidation Forming), with 2-D innovative material for covers
3. Near-Term – Represents concepts that utilize integral 3-D woven covers using commingled graphite and thermoplastic fiber.

TABLE 29 CONCEPT SELECTION, MULTI-SPAR CONCEPTS

PARAMETERS	WEIGHTING FACTOR	CONCEPT I IM7/8551-7A SYNCORE-STIFFENED			CONCEPT II G40-800/F584 SYNCORE-STIFFENED			CONCEPT IV G40-800/F584 SPREAD 0°/Y-SPARS			CONCEPT V G40-800/F584 DISCRETE CAP/Y-SPARS		
		TOTAL SCORE	NO. OF R	AVG. SCORE	TOTAL SCORE	NO. OF R	AVG. SCORE	TOTAL SCORE	NO. OF R	AVG. SCORE	TOTAL SCORE	NO. OF R	AVG. SCORE
WEIGHT	25	450	4	113	700	4	175	575	4	144	675	4	169
RISK	10	300	4	75	300	4	75	240	4	60	240	4	60
MFG RDT & E AND PRODUCTION COSTS	18	552	4	138	528	4	132	552	4	138	552	4	138
DURABILITY & SURVIVABILITY	14	378	4	95	364	4	91	378	4	95	406	4	102
REPAIRABILITY	15	435	4	109	435	4	109	405	4	101	420	4	105
INSPECTION/ACCESS	10	290	4	73	290	4	73	220	4	55	220	4	55
OPS & SUPT COSTS	8	224	4	56	224	4	56	236	4	59	236	4	59
SUM OF AVG. SCORES				659			711			652			688

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TABLE 30 CONCEPT SELECTION, MULTI-RIB CONCEPTS

		CONCEPT III			CONCEPT VI		
PARAMETERS	WEIGHTING FACTOR	IM7/TACTIX 123 HAT-STIFFENED			IM7/TACTIX 123 Y-STIFFENED		
		TOTAL SCORE	NO. OF R	AVG. SCORE	TOTAL SCORE	NO. OF R	AVG. SCORE
WEIGHT	25	700	4	175	925	4	231
RISK	10	250	4	63	250	4	63
MFG RDT & E AND PRODUCTION COSTS	18	456	4	114	480	4	120
DURABILITY & SURVIVABILITY	14	406	4	102	364	4	91
REPAIRABILITY	15	405	4	101	390	4	98
INSPECTION/ACCESS	10	260	4	65	250	4	63
OPS & SUPT COSTS	8	245	4	61	212	4	53
SUM. OF AVG. SCORES				681			719

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A concept, from each of the three development states, was then selected. Concepts I and II were categorized under the first development stage. With Concept II scoring a higher rating than Concept I, it is the selected concept within this classification. For the In-Development stage, Concepts IV and V were compared. Concept V received a higher rating and, therefore, it is the selected concept. The concepts within the last classification of development, Near-Term, are III and VI, with Concept VI receiving the higher score of the two.

The relative closeness of the ratings for Concepts II, V, and VI and the subjective nature of the evaluation make them virtually equivalent. However, continued effort will be directed towards Concepts V (Multi-Spar: Y-Spar) and VI (Multi-Rib: Y-Stiffened), since they represent the latter stages of development and have the most potential to attain the program's goals.

3 – SUBTASK 2: INTERMEDIATE WING Y-SPAR DESIGN

Based on the results of the evaluation of the combined material/configuration concepts, the Y-spar was selected for further study. A Y-spar representative of an intermediate wing spar segment in size, complexity, and load-carrying capability (shear flow of 1,015 lb/in. in five-spar wing configuration) was designed, Drawing D19B8220, Fig. 24.

3.1 FIBER ARCHITECTURE OF Y-SPAR PREFORMS

3.1.1 Woven Commingled AS4/PEEK

In order to achieve the target in fiber architecture, a series of steps that Textile Technologies, Inc., (TTI), the subcontractor, was to take in designing and fabricating three (3) AS4 6K/PEEK 150 g and three (3) IM7 12K multilayered Y-spar preforms was specified:

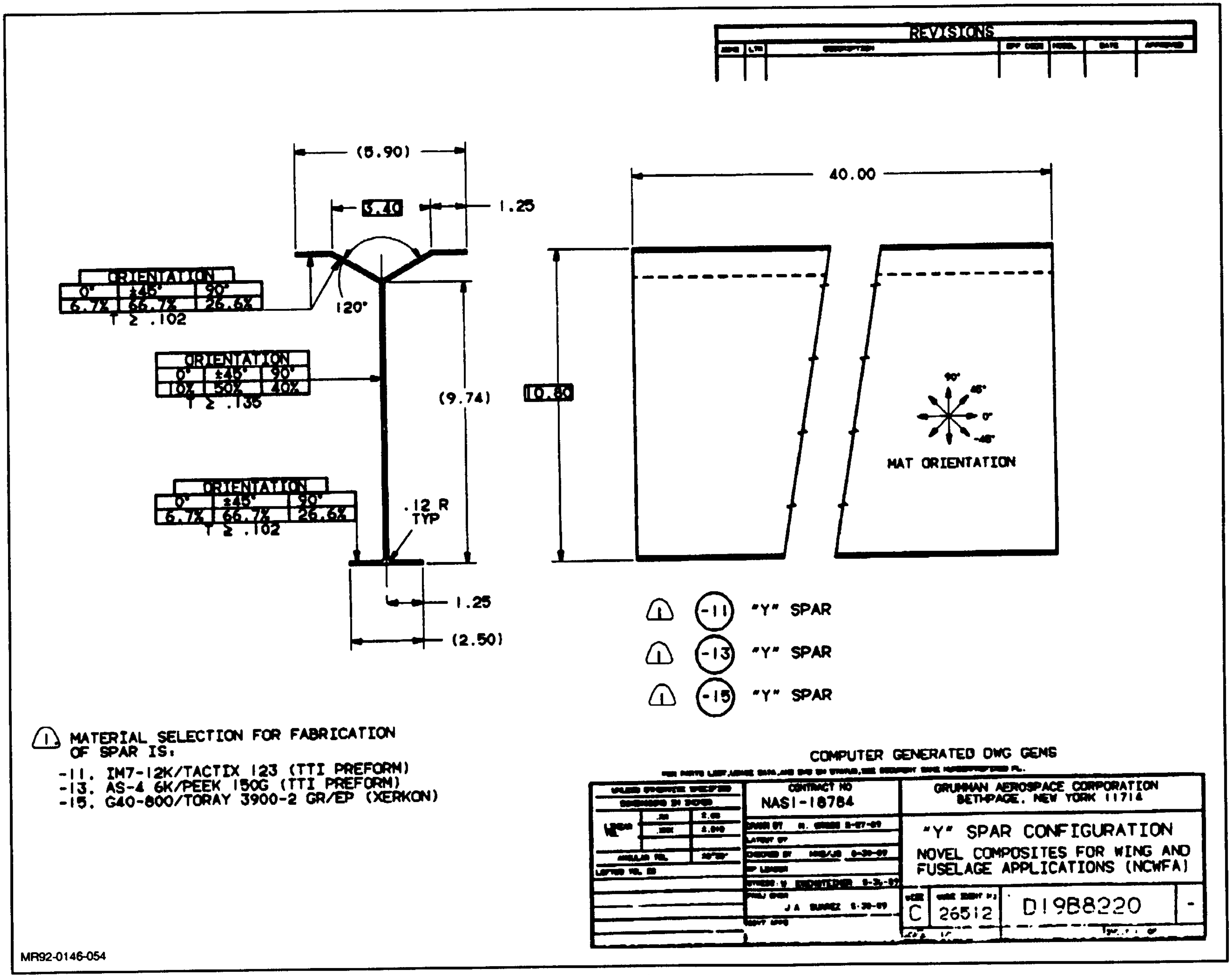
1. All tolerances of dry woven thickness will be specified on TTI's drawing.
2. TTI shall attempt to obtain a high areal weight to permit a 60±2% volume fraction laminate. TTI will specify the value obtained for each material's fiber architecture. The planned architecture is to provide a maximum of 5% by volume of fibers through the thickness to maintain high in-plane properties.
3. TTI will provide small panels for obtaining mechanical properties test data. If material remains after the fabrication of the Y-spars, TTI will fabricate small test panels of a similar fiber architecture to the Y-spars. The panel dimensions and quantities will be determined by TTI.
4. TTI will submit fiber architectural drawings to Grumman. Grumman will analyze the architecture and discuss results with TTI's Engineering Department. Based on the outcome of these discussions, TTI will fabricate in one setup the AS4 6K/PEEK and IM7 12K Y-spar preforms.

The architecture of the woven commingled AS4/PEEK 150g 0°/90° preforms is presented in Fig. 25. The preform webs consist of 76.59 percent fill yarns, 19.14 percent warp stuffers, and 4.25 percent through-the-thickness warp weavers. The preform flanges consist of 75.00 percent fill yarns, 18.75 percent warp stuffers, and 6.25 percent through-the-thickness warp weavers.

The critical dimension for the preforms was the web height as measured from the centerline of the 90-degree flange to the centerline of the Y-flange, i.e., 10.70 in. This dimension was made important by the decision to use male mandrels for consolidation of the preforms. Web and flange thicknesses were to be such that, upon preform consolidation to a 60 percent fiber volume, target dimensions would be achieved.

The Y-spar 0°/90° carcasses were woven by TTI using a Jacquard loom. Sewing Machine Exchange, Inc. (SMX), a TTI subcontractor, stitched woven commingled AS4/PEEK 150g fabric in 45°/135° orientations to the carcasses to provide 40 in. (length) woven/stitched 3-D Y-spar preforms.

The framework printout for the web of the commingled AS4/PEEK 150g 0°/90° Y-spar preforms is shown in Table 31. The 27 ends/in. end count for the warp fibers was composed of 22 warp stuffers and five through-the-thickness weavers. The denier value for the AS4 and PEEK 150g fibers making up the tows used in the warp and fill directions were 3927 and 1800, respectively. Target thickness and percent fiber volume values for the consolidated web were 0.071 in. and 61.0 percent, respectively.


REVISIONS
(5.90)
3.40
1.25
ORIENTATION
0° | ±45° | 90°
6.7% | 66.7% | 26.6%
T ≥ .102
120°
ORIENTATION
0° | ±45° | 90°
10% | 50% | 40%
T ≥ .135
(9.74)
ORIENTATION
0° | ±45° | 90°
6.7% | 66.7% | 26.6%
T ≥ .102
.12 R
TYP
1.25
(2.50)
40.00
10.80
90°
45°
0°
-45°
MAT ORIENTATION
1 -11 "Y" SPAR
1 -13 "Y" SPAR
1 -15 "Y" SPAR
1 MATERIAL SELECTION FOR FABRICATION
OF SPAR IS:
-11. IM7-12K/TACTIX 123 (TTI PREFORM)
-13. AS-4 6K/PEEK 150G (TTI PREFORM)
-15. G40-800/TORAY 3900-2 GR/EP (XERKON)
COMPUTER GENERATED DWG GENS
CONTRACT NO
NAS1-18784
GRUMMAN AEROSPACE CORPORATION
BETHPAGE, NEW YORK 11714
"Y" SPAR CONFIGURATION
NOVEL COMPOSITES FOR WING AND
FUSELAGE APPLICATIONS (NCWFA)
J A SUAREZ
C
26512
D19B8220
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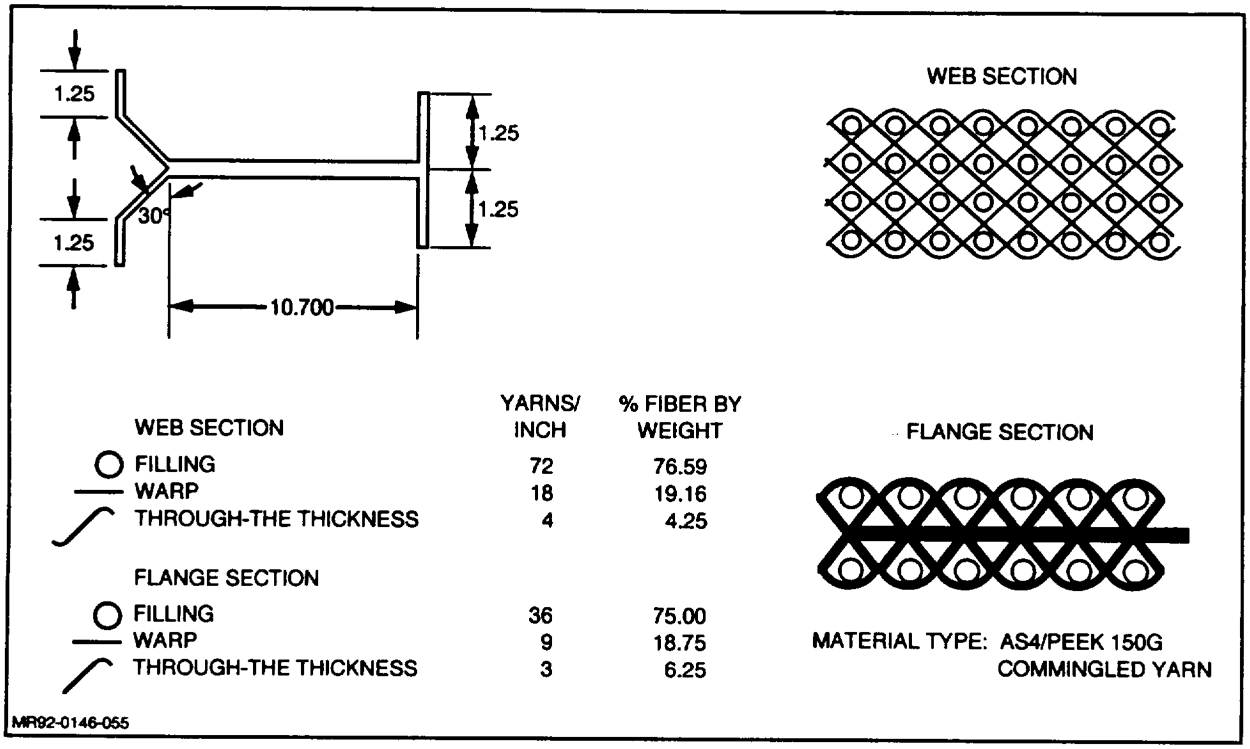
MR92-0146-054

Fig. 24 Y-Spar



	YARNS/ INCH	% FIBER BY WEIGHT
WEB SECTION		
O FILLING	72	76.59
— WARP	18	19.16
THROUGH-THE THICKNESS	4	4.25
FLANGE SECTION		
O FILLING	36	75.00
— WARP	9	18.75
THROUGH-THE THICKNESS	3	6.25

MATERIAL TYPE: AS4/PEEK 150G COMMINGLED YARN

Fig. 25 Architecture of Woven Commingled AS4/PEEK 150G 0°/90° Preform

TABLE 31 WOVEN COMMINGLED 3-D AS4/PEEK 150 G 0°/90° Y-SPAR WEB PREFORM

HYBRID YARN FABRIC			FIBER	RESIN	TOTAL	
WARP	• END COUNT	(ENDS/IN)	27	27		
	• MANUFACTURER		BASF *	BASF/ PEEK		
	• PRODUCT CODE		AS-4 6K			
	• DENIER	(GR/M	3927	1800	5727	
	• YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	• AREAL WEIGHT	(GR/SQ M)	463.8	212.6	676.4	19.93
	• THICKNESS	(MILS)	10.1	6.5	16.6	^OZ/SQ YD^
	• VOLUME FRACTION	(%)	14.3	9.2	23.5	
	• WEIGHT FRACTION	(%)	16.1	7.4	23.5	
FILL	• END COUNT	(ENDS/IN)	88	88		
	• MANUFACTURER		BASF *	BASF/ PEEK		
	• PRODUCT CODE		AS-4			
	• DENIER	(GR/M	3927	1800	5727	
	• YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	• AREAL WEIGHT	(GR/SQ M)	1511.7	692.9	2204.6	64.96
	• THICKNESS	(MILS)	33.1	21.1	54.2	^OZ/SQ YD^
	• VOLUME FRACTION	(%)	46.7	29.9	76.5	
	• WEIGHT FRACTION	(%)	52.5	24.1	76.5	
TOTAL FABRIC	AREAL WEIGHT	(GR/SQ M)	1975.5	905.5	2881.0	84.89
	THICKNESS	(MILS)	43.2	27.6	70.8	^OZ/SQ YD^
	VOLUME FRACTION	(%)	61.0	39.0	100	
	WEIGHT FRACTION	(%)	68.6	31.4	100	
	DENSITY	(GR/CC)			1.60	

* PEEK IN FIBER FORM

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Similarly the framework printout for the flange of the commingled AS4/PEEK 150g 0°/90° Y-spar preforms is shown in Table 32. The 15 ends/in. end count for the warp fibers was composed of warp stuffers and through-the-thickness weavers. The denier value for the AS4 and PEEK 150g fibers making up the tows used was again 3927 and 1800, respectively. Target thickness and percent fiber volume values for the consolidated 0°/90° Y-spar web carcass were 0.036 in. and 61.0 percent, respectively.

TABLE 32 WOVEN COMMINGLED 3-D AS4/PEEK 150 G 0°/90° Y-SPAR FLANGE PREFORM

HYBRID YARN FABRIC			FIBER	RESIN	TOTAL	
WARP	• END COUNT	(ENDS/IN)	15	15		
	• MANUFACTURER		BASF *	BASF/ PEEK		
	• PRODUCT CODE		AS-4 6K			
	• DENIER	(GR/M)	3927	1800	5727	
	• YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	• AREAL WEIGHT	(GR/SQ M)	257.7	118.1	375.8	11.07
	• THICKNESS	(MILS)	5.6	3.6	9.2	^OZ/SQ YD^
	• VOLUME FRACTION	(%)	15.5	9.9	25.4	
	• WEIGHT FRACTION	(%)	17.4	8.0	25.4	
FILL	• END COUNT	(ENDS/IN)	44	44		
	• MANUFACTURER		BASF *	BASF/ PEEK		
	• PRODUCT CODE		AS-4			
	• DENIER	(GR/M)	3927	1800	5727	
	• YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	• AREAL WEIGHT	(GR/SQ M)	755.9	346.5	1102.3	32.48
	• THICKNESS	(MILS)	16.5	10.6	27.1	^OZ/SQ YD^
	• VOLUME FRACTION	(%)	45.5	29.1	74.6	
	• WEIGHT FRACTION	(%)	51.1	23.4	74.6	
TOTAL FABRIC	AREAL WEIGHT	(GR/SQ M)	1013.5	464.6	1478.1	43.55
	THICKNESS	(MILS)	22.2	14.2	36.3	^OZ/SQ YD^
	VOLUME FRACTION	(%)	61.0	39.0	100	
	WEIGHT FRACTION	(%)	68.6	31.4	100	
	DENSITY	(GR/CC)			1.60	

* PEEK IN FIBER FORM

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3.1.2 Woven IM7 Graphite

The design and fabrication of the IM7 12K angle-interlock woven Y-spar preforms was similar to that described above for the AS4 6K/PEEK 150g preforms. The 0°/90° woven carcass was stitched to the ±45° fabric using either fiberglass or Toray graphite threads to provide 3-D Y-spar preforms.

3.1.3 Knitted/Stitched G40-800 Graphite

The knitted/stitched G40-800 graphite Y-spar preforms were designed and fabricated using no-crimp architecture as shown in Fig. 26. The fabric is a reinforcement consisting of multiple layers of discreet, nonintersecting unidirectional plies, interconnected by out-of-plane binder yarns. These stacks of no-crimp layers with straight fiber bundles are next stitched with fiberglass or H.S. Toray thread to form the Y-spar preform.

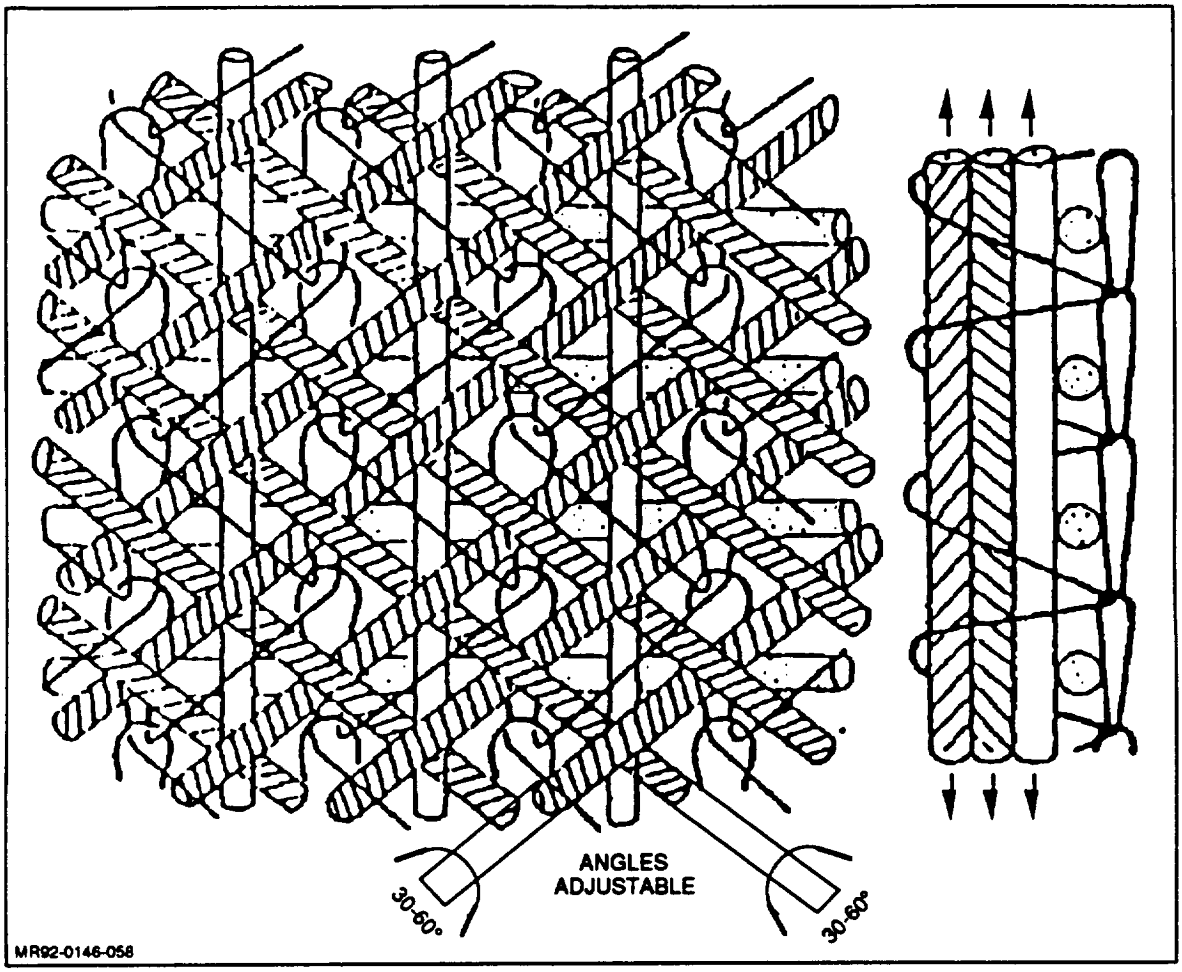

Fig. 26 Schematic of No-Crimp Knitting Architecture

Figures 27 and 28, together with Tables 33-35, show the graphite fiber orientation, percent weight and predicted ply cured thickness. Due to an error by Compositek, Inc, in fabricating these preforms, the Y-spars fabricated had the fiber architecture denoted by ACTUAL in Tables 33-35. The differences were found to be acceptable and the preforms were subsequently processed.

3.2 Y-SPAR TEST SPECIMENS

The design of composite covers for use in the four-point beam bending of the "Y"-spar test specimens employed IM6/3501-6 Gr/Ep tape. The covers are mechanically fastened to the "Y"-spar flange using 1/4-in. diameter titanium Hi-Lok fasteners.

The cover design was established maintaining a minimum factor of safety of two (FS $\geq$ 2.0) on the critical (ε_{ult} = 6,000 μin./in.) loading. A thirty (30) ply laminate was required to satisfy these criteria with a stacking sequence of $[\pm 45_2, 0_2, \pm 45_2, 90_2, \pm 45, 90]_s$. The same laminate was used for both the upper and lower covers.

Results of the buckling stability, notched strain allowable, and bolt bearing allowable analyses are given in Tables 36 to 38. The bearing analysis performed on the "Y"-spar makes use of the ultimate bearing load for AS4/3501-6 fabric with a knockdown factor of 10%. This was assumed, in the absence of test data, for the "Y"-spar material.

Figure 29 gives the geometry of the test specimen and the loading schematic to be employed in the four-point beam bending test. The intermediate spar shear design ultimate load of 1015 lb/in. is reacted entirely by the covers.

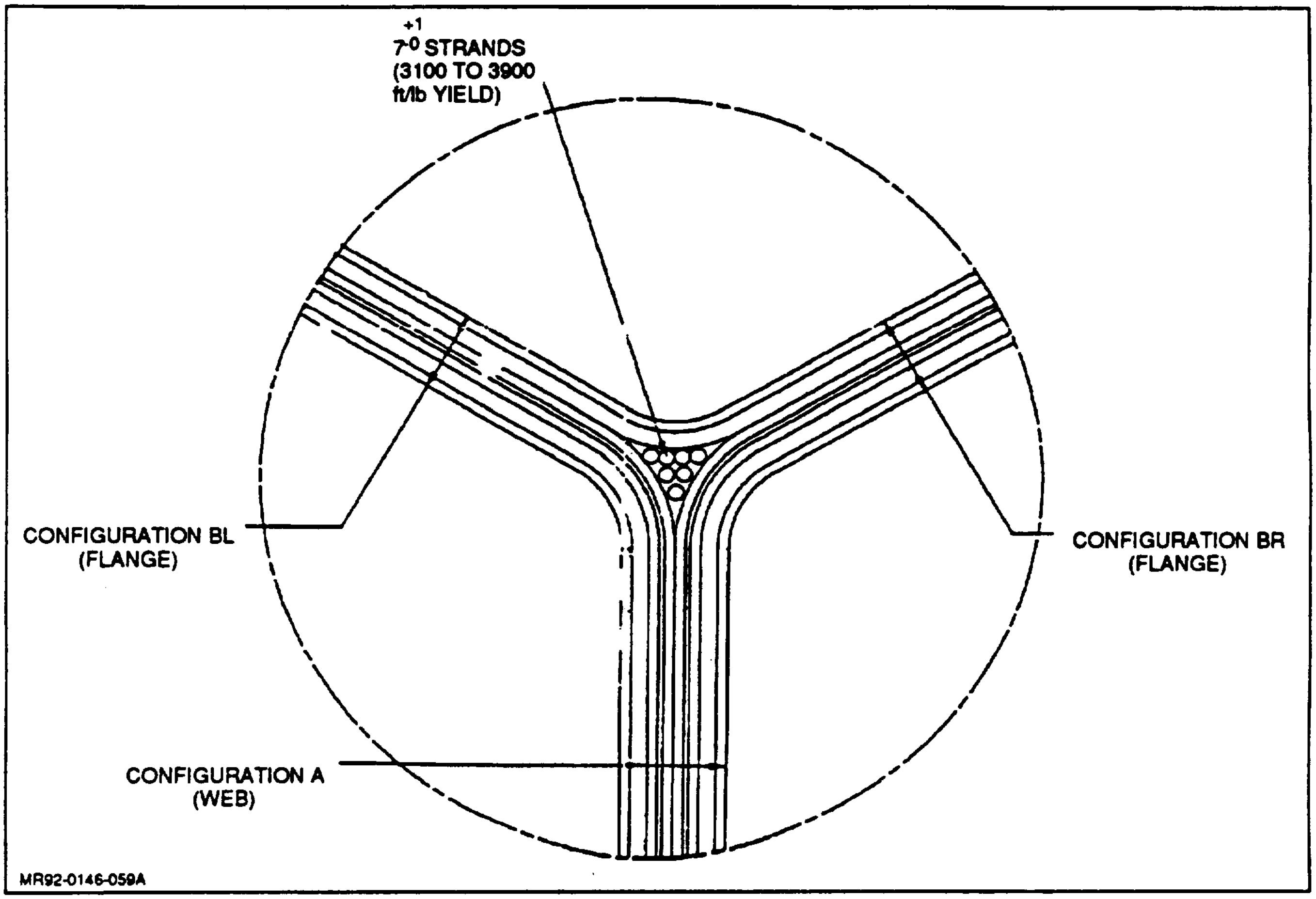

Fig. 27 Knitted/Stitched G40-800 Graphite Y-Flange Architecture

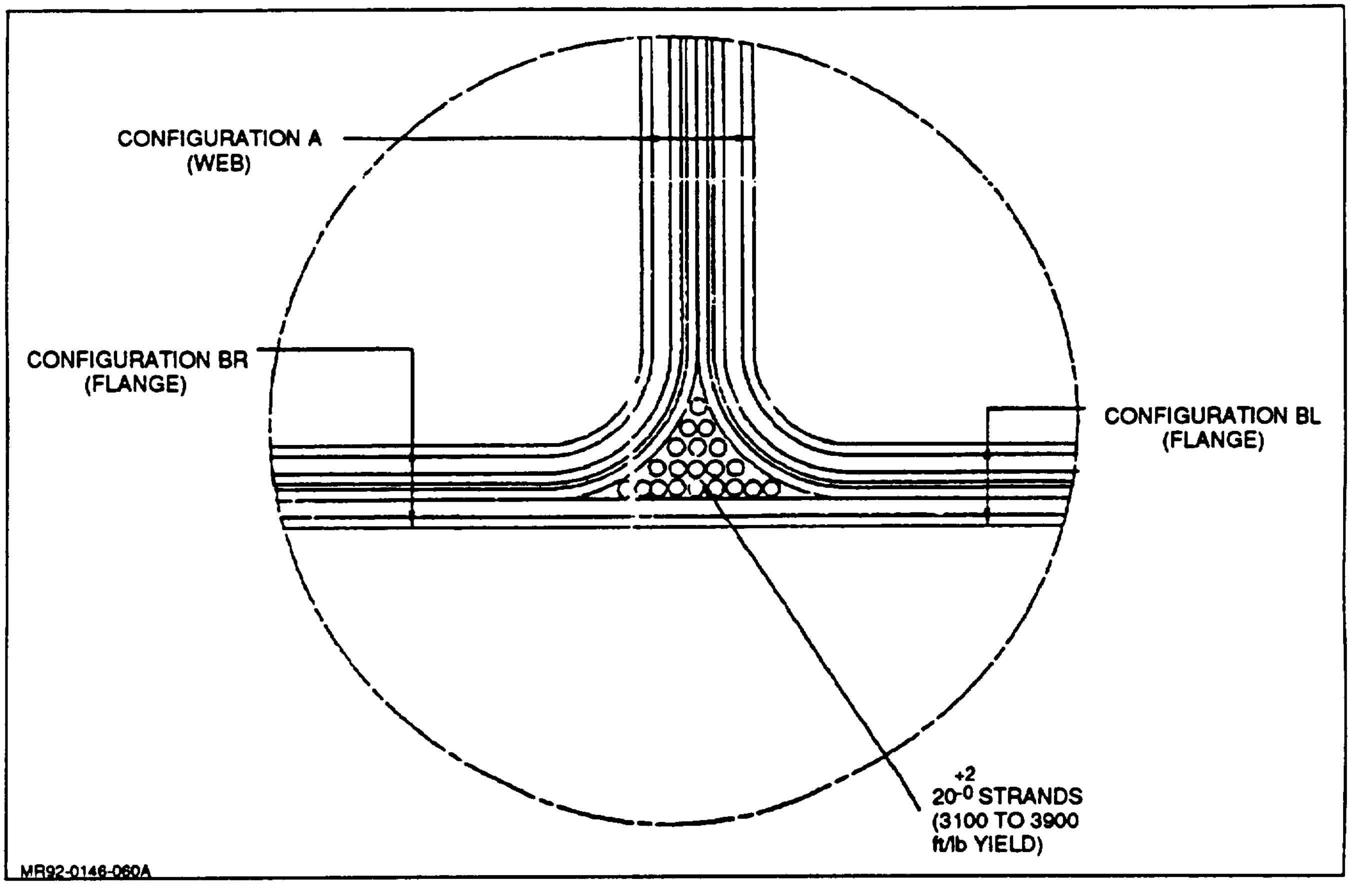

Fig. 28 Knitted/Stitched G40-800 Graphite Tee-Flange Architecture

TABLE 33 KNITTED/STITCHED Y-SPAR WEB CONFIGURATION

CONFIGURATION "A" (WEB)					
PLY NO.	ORIENTATION	AREAL WEIGHT / PLY, gm/m^2		PLY THICKNESS, in.	
		THEORY	ACTUAL	THEORY	ACTUAL
1	±45°	345.9	370	0.01334	0.01427
2	90°	572.5	517	0.02208	0.01994
3	∓45°	345.9	370	0.01334	0.01427
4	0°	178.9	162	0.00690	0.00624
5	±45°	345.9	370	0.01334	0.01427
6	∓45°	345.9	370	0.01334	0.01427
7	0°	178.9	162	0.00690	0.00624
8	±45°	345.9	370	0.01334	0.01427
9	90°	572.5	517	0.02208	0.01994
10	∓45°	345.9	370	0.01334	0.01427
MR92-0146-061	TOTAL	3578	3578	0.138	0.138

TABLE 34 KNITTED/STITCHED Y-SPAR FLANGE CONFIGURATION

CONFIGURATION "BL" (FLANGE)					
PLY NO.	ORIENTATION	AREAL WEIGHT / PLY, gm/m^2		PLY THICKNESS in.	
		THEORY	ACTUAL	THEORY	ACTUAL
1	±45°	345.9	370	0.01341	0.01452
2	90°	572.5	517	0.02220	0.02028
3	±45°	345.9	370	0.01341	0.01452
4	0°	178.9	162	0.00694	0.00636
5	±45°	345.9	370	0.01341	0.01452
6	90°	572.5	517	0.02220	0.02028
7	±45°	345.9	370	0.01341	0.01452
MR92-0146-062	TOTAL	2707	2676	(0.105)	(0.105)

TABLE 35 KNITTED/STITCHED Y-SPAR TEE FLANGE CONFIGURATION

CONFIGURATION "BR" (FLANGE)					
PLY NO.	ORIENTATION	AREAL WEIGHT / PLY, gm/m^2		PLY THICKNESS in.	
		THEORY	ACTUAL	THEORY	ACTUAL
1	±45°	345.9	370	0.01341	0.01452
2	90°	572.5	517	0.02220	0.02028
3	±45°	345.9	370	0.01341	0.01452
4	0°	178.9	162	0.00694	0.00636
5	±45°	345.9	370	0.01341	0.01452
6	90°	572.5	517	0.02220	0.02028
7	±45°	345.9	370	0.01341	0.01452
MR92-0146-063	TOTAL	2707	2676	0.105	0.105

TABLE 36 COMPRESSION COVER STRENGTH AND BUCKLING ANALYSIS

COMPRESSION COVER	LAMINATE [0/90 /± 45]		
	[4/6/20]	[4/2/24]	[3/2/24]
P_x DUL	-12,180	-12,180	-12,180
P_{xcr}* lb	-27,000	-28,300	-25,600
$SF_{Buckling}$	2.22	2.32	2.10
ε_x^c, μ in./in.	-2130	-2230	-2530

*CRITICAL PANEL BUCKLING LOAD

MR92-0146-064A

TABLE 37 TENSION COVER LOADED HOLE STRAIN ALLOWABLE

TENSION COVER	LAMINATE [0/90/±45]		
	[4/6/20]	[4/2/24]	[3/2/24]
N_xDUL, lb/in.	4872	4872	4872
P_{bx}, lb	634.4	634.4	634.4
ε_x^t, μin./in.	4670	4940	5620
M.S.	0.20	0.16	0.032

MR92-0146-065

TABLE 38 BOLT BEARING

LAMINATE [0/90/±45] – [4/6/20]			
	COVER	FLANGE	WEB
D_f, in.	0.25	0.25	0.375
P_{bx} DUL, lb	634.4	634.4	1370
P_{BRU}, lb	3523	1318*	2795*
SF_{Br}	5.55	2.08	2.04

*VALUE FOR AS4/3501-FABRIC WITH A 10% KNOCKDOWN

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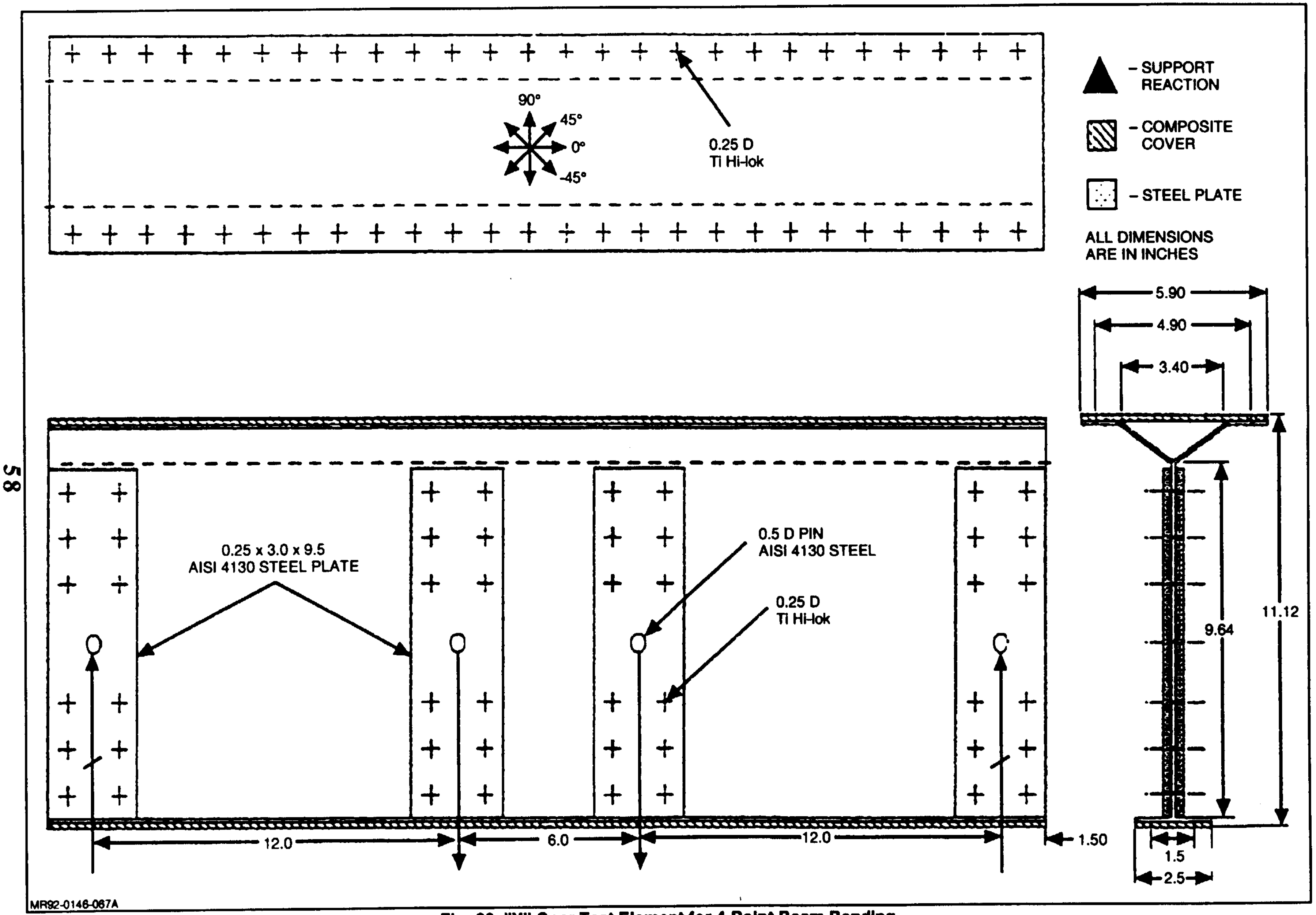

Fig. 29 "Y"-Spar Test Element for 4-Point Beam Bending

4 – SUBTASK 3: FABRICATION OF Y-SPARS

4.1 MANUFACTURING STUDIES

Per the program's Design/Manufacturing Integration (D/MI) Plan, parts with the chosen "Y"-spar configuration were fabricated using newly emerging structurally efficient material forms and with innovative manufacturing procedures. These state-of-the-art technologies are the primary output of the Task 1 activities.

Advanced material forms and processes with documented potential for cost-effective use in the construction of structurally efficient wing structure were screened during Task 1. The manufacturing studies identified the following materials and low-cost processes for consideration in this program:

- Materials
  - IM7 fiber
  - AS4 fiber
  - G40-800 fiber
  - Commingled yarns of AS4 and PEEK fibers
  - Improved resin transfer molding (RTM) resin systems
    - * Dow Tactix 123/H41
    - * Shell Epon DPL 862/W
    - * 3M Scotchply PR500
    - * BP Chemicals E905L A/B
- Processes
  - Weaving/Stitching
  - Knitting/Stitching
  - RTM
  - Resin Film Infusion (RFI)/Autocomp (Xerkon)
  - Consolidation.

Combinations of the above materials and processes were used to fabricate the Task 1 "Y"-spars, as detailed in succeeding subsections.

4.2 "Y"-SPAR FABRICATION

The D/MI Plan originally called for the fabrication and testing of three types of "Y"-spar, as listed below:

- Woven/stitched IM7 preform impregnated by Grumman with Dow Tactix 123/H41 resin system using RTM procedures
- Woven/stitched commingled/AS4 PEEK preform thermoformed (consolidated) by Grumman
- Knitted/stitched G40-800 preform impregnated with Toray 3900-2 resin system via Resin Film Infusion (RFI), then Autocomp-processed by Xerkon (Compositek Corporation).

As the program progressed, technical considerations that developed necessitated some minor modifications to the original plan. The basic three processes, however, remained essentially intact, with some changes in resin systems used in each. These changes are discussed at length in later subsections of this report.

Concurrent with the fabrication of the RTM-processed spars, studies were made of the candidate resin systems listed earlier. These studies will be described in some detail in the next subsection.

4.2.1 Resin Transfer Molding (RTM) Studies

In support of the RTM fabrication of the "Y"-spars, a series of RTM studies was initiated in order to explore the applicability of several candidate resin systems to the RTM-processed "Y"-spars. These studies involved the fabrication of a series of 13-by-15-in. flat panels using an aluminum RTM tool made available to the program. (Due to concerns about the aluminum tools' rigidity, it was ultimately replaced with a similar tool made of steel.) Each of the studies' panels was fabricated using a preform of 14 plies of AS4 (CSW) fabric, laid up in a 0-deg/90-deg orientation and stitched together using Kevlar thread. The graphite preforms were then impregnated at Grumman using a Hypaject 3LMKI Model 30 injection system (see Fig. 30). Vendor-supplied physical and mechanical properties data for the candidate resin systems are presented in Table 39. Also shown are target values for a "best" resin system, as visualized by Grumman, for comparison.

Each of the completed panels was then sectioned into coupons for physical properties testing (fiber, resin, and void content) and mechanical properties testing (horizontal shear strength). Data generated in Grumman's RTM studies are shown in Table 40. (Due to a premature curing problem with BP Chemicals E905L resin, studies involving this resin system are incomplete; therefore, data on it are not listed.)

4.2.2 D19B8220-11 "Y"-Spar Fabrication (RTM)

This effort involved the RTM impregnation of woven/stitched IM7 12K "Y"-spars with Dow Tactix 123 resin and H41 catalyst. The configuration of these spars is shown in Fig. 24, the Grumman Engineering Drawing. Several subcontractors were involved in this fabrication effort, as described below.

The 0-deg/90-deg carcasses were woven by Textile Technologies, Inc. (TTI), Hatboro, PA, on a Jacquard loom. This fully automatic weaving system involves the use of a series of punched cards to control the carcass's architecture based on Engineering requirements. The ±45-deg ply material was then located on the outside faces of both the webs and the flanges of the completed carcasses by TTI. The ±45-deg plies were then semiautomatically stitched in place by Ketema, Textile Products Div., Anaheim, CA, using Toray T900-1000A fiber. (The stitching operation was necessitated by the fact that weaving is currently limited to 0-deg and 90-deg orientations). This completed the preforms, which were then shipped back to TTI for removal of a PVA serving from the yarns. This serving, which is required to maintain integrity of the yarns during the weaving operations, was boiled off in multiple steps in large tanks. After TTI's quality checks, the preforms were shipped to Grumman for inspection.

Concurrently, in preparation for the RTM processing of these preforms, Compositek Corporation, Brea, CA, was designing and fabricating the tooling required for their impregnation with Dow Tactix 123/H41 resin. The tooling would be made of aluminum and provide completed parts to net trim per our Engineering Drawing (Fig. 24). (Although Grumman was originally planning on fabricating the RTM-processed "Y"-spars, due to limitations of our present RTM equipment it was decided to subcontract the RTM effort to a firm that specializes in RTM tooling and processing. Compositek was chosen for this task).

Unfortunately, during inspection of the first preform, it was discovered that the TTI woven carcasses were not correct. Thorough checking revealed that they were oversize and too thick. Specifically, the vertical web heights, which were targeted to be 9.638 in., were woven between 10.5 and 11.0 in. Additionally, both the webs and the flanges of the carcasses were thicker than was originally called for.

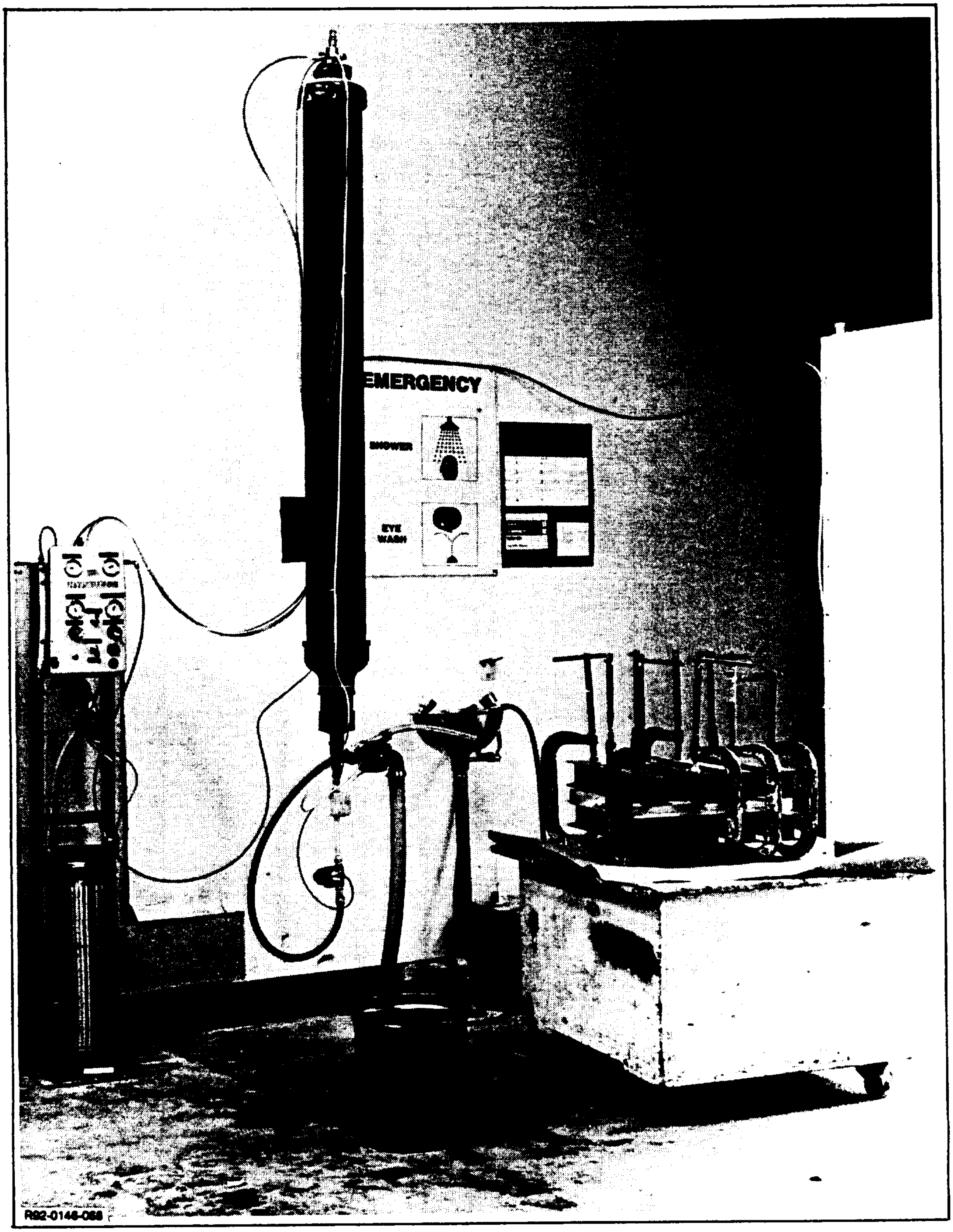

Fig. 30 Grumman's RTM Injection Equipment

TABLE 39 BULK, PHYSICAL, AND MECHANICAL PROPERTIES OF CANDIDATE AND TARGET RTM RESIN SYSTEMS

SYSTEM			PROCESS PARAMETERS						COMPRESSION					
									STRENGTH		MODULUS			
MANUF.	RESIN	HARDENER	RTM TEMP, °F	RTM VISCOSITY, cp	POT LIFE, hr	CURE, hr/°F	POST CURE TIME AT TEMP, hr/°F	TG, °F	RT, ksi	HOT/WET, ksi	RT, msi	HOT/WET, msi	CAI[5], ksi	SERVICE TEMP RANGE
TARGET SYSTEM (ONE COMPONENT)			≤200	≤20	≥4	≤2/ ≤250	≤4/ ≤350	>400	>100[1]	>80[1]	>10[1]	>9[1]	40	-67°F TO 180°F
DOW	TACTIX 123	H41	120	210	3.2	1/250	3/350	331[1]	96[1]	66[1]	TBD	TBD	TBD	-67°F TO 220°F
SHELL	DPL862	W (DPC 763)	250	10	1.5	1/350	3/350	322[2]	TBD	TBD	TBD	TBD	TBD	-67°F TO 220°F
3M	PR500	NONE	230	300	8.0	2/350	NONE	401[3]	123[3]	TBD	TBD	TBD	TBD	-67°F TO 300°F
USP	E905L (A)	E905L (B)	200	200	2.0	2/350	NONE	383	114[4]	87[4]	10.2[4]	10.3[4]	27[4]	-67°F TO 220°F

NOTES
1. FABRIC IS HERCULES AS4 8HS-3K (62% FIBER VOLUME/NORMALIZED)
2. FABRIC IS CELION G30-500 8H-3K
3. FABRIC IS CELION 3000 8HS-3K
4. FABRIC IS CELION 3000 8HS (60% FIBER VOLUME/NORMALIZED)
5. COMPRESSION AFTER IMPACT: 1500 IN.-LB/IN.

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TABLE 40 PHYSICAL AND MECHANICAL PROPERTIES OF RTM TEST PANELS

PROPERTY / MATERIAL	LAMINATE PHYSICAL PROPERTIES				HORIZONTAL SHEAR STRENGTH, ksi	
	PER-PLY THICKNESS RANGE, mils	PERCENT FIBER VOLUME, %	PERCENT RESIN CONTENT, %	PERCENT VOID CONTENT, %	ROOM TEMP	200°F
TARGET VALUES (1)	6.6 – 7.8	> 56.9	42.9	0.2	> 9.0	> 7.5
DOW TACTIX 123/ H41, PANEL 1 (2)	7.1 – 8.7	46.3	52.8	0.9	6.9	6.1
DOW TACTIX 123/ H41, PANEL 2 (2)	6.9 – 7.6	53.9	45.5	0.6	7.7	6.6
SHELL DPL862/ W, PANEL 1 (2)	7.0 – 7.3	52.4	47.2	0.4	9.3	6.5
SHELL DPL862/ W, PANEL 2 (2)	–	53.9	45.0	1.1	9.6	5.8
3M SCOTCHPLY PR-500, PANEL 1 (2)	7.6 – 7.9	52.3	47.7	0.0	11.7	8.2
3M SCOTCHPLY PR-500, PANEL 2 (2)	7.5 – 7.8	50.8	48.3	0.9	10.4	7.8

NOTES: 1. AS4 (CSW)/3501-6 AUTOCLAVE-CURED LAMINATE
2. AS4 (CSW) PREFORM

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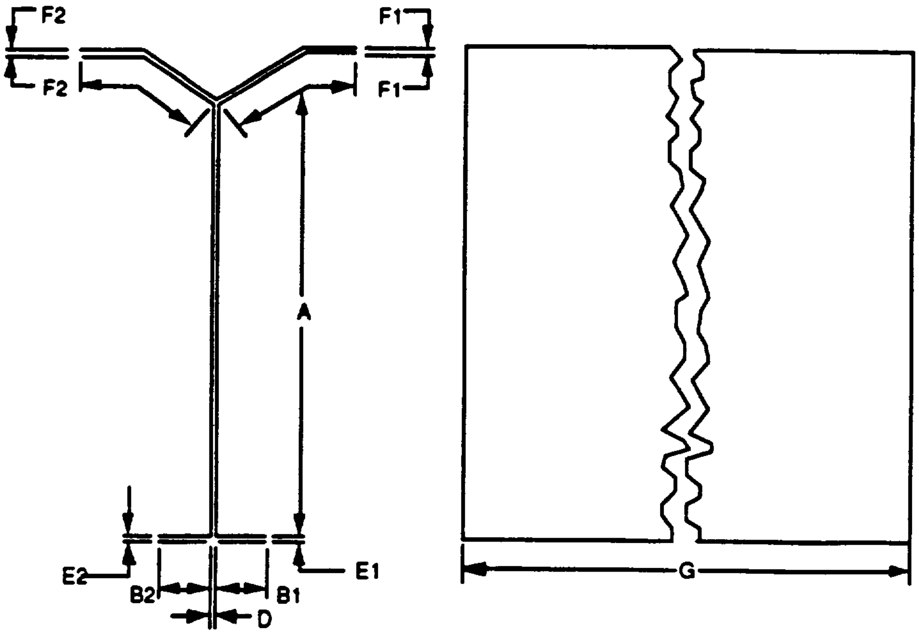
Figure 31 provides both the target and actual dimensions for the two TTI/Ketema preforms. TTI's quality assurance checks corroborated the discrepancies identified by Grumman.

In an effort to determine how the overthick webs would impact the ability to fit the preforms into Compositek's RTM tool, load deflection determinations were performed on the webs of both preforms. Web thickness values versus applied stress for the first preform are shown in Fig. 32. These values indicate that, at an applied stress of 1800 psi, the web thickness of the "Y"-spar would be approximately 0.200 in., rather than the target dimension of 0.135 in. Based on the load deflection measurements, it would not be possible to install these preforms in the RTM tool designed to satisfy the as-designed configuration of the D19B8220-11 Engineering Drawing.

In a joint effort to determine what caused the problems with the preforms, Grumman calculated the part's theoretical volume and, from this, the weight of the dry preform. These data were reported to TTI, along with the actual weights of both preforms (6.13 lb and 5.81 lb, respectively). TTI's investigation of their processing records indicated that the IM7 spar carcasses (0-deg/90-deg) were woven at 22 picks per inch (ppi), not at 11 ppi as was called for by these structures' architecture.

In order to accommodate the oversize/overweight preforms, several actions were taken:

- The tool fabricated by Compositek was modified via a removable shimming arrangement to allow for the extra thickness. The extra web height necessitated that the "Y"-spars' T-flanges be cut off, and the extra sections of web discarded
- TTI fabricated a replacement woven IM7 3-D preform to satisfy the requirements of the engineering drawing. It was then sent to Ketema for stitching of the ±45-deg plies. Due to a program de-



PREFORM DIMENSION MEASURED	Y-SPAR DIM. REQUIRED, In.	IM7 "Y"-SPAR PREFORM	
		PREFORM 1, In.	PREFORM 2, In.
A	9.638	10.75-11.00	10.50-10.75
B1	1.25	1.38	1.00
B2	1.25	0.0 (MIN)-0.75	1.13
C1	3.21	2.63 (MIN)	2.63 (MIN)
C2	3.21	2.63 (MIN)	2.63 (MIN)
D	0.135	0.32-0.36	0.31-0.39
E1	0.102	0.29-0.34	0.27-0.29
E2	0.102	0.29-0.34	0.29-0.32
F1	0.102	0.32-0.36	0.29-0.34
F2	0.102	0.35-0.40	0.30-0.33
G	40	44.50	43.75

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Fig. 31 Woven IM7 3-D 'Y' Spar Dimensional Analysis

cision, it was then impregnated by Compositek via their RFI/Autocomp processing techniques. (This effort is further described later in this report).

Despite the modification of their RTM tool to the theoretical thicknesses that the oversize preforms should have achieved, Compositek reported that it was still not possible to fully close the tool around the preforms. As a result, they were instructed to proceed with the "Y"-spar fabrication on a best-effort basis. With this understanding, they processed the two spars.

With the help of a 150-ton press to force the tool's details closed, Compositek fabricated both IM7 preforms, impregnating them with Dow Tactix 123/H41 resin. Unfortunately, both attempts were not very successful, producing parts of extremely poor quality.

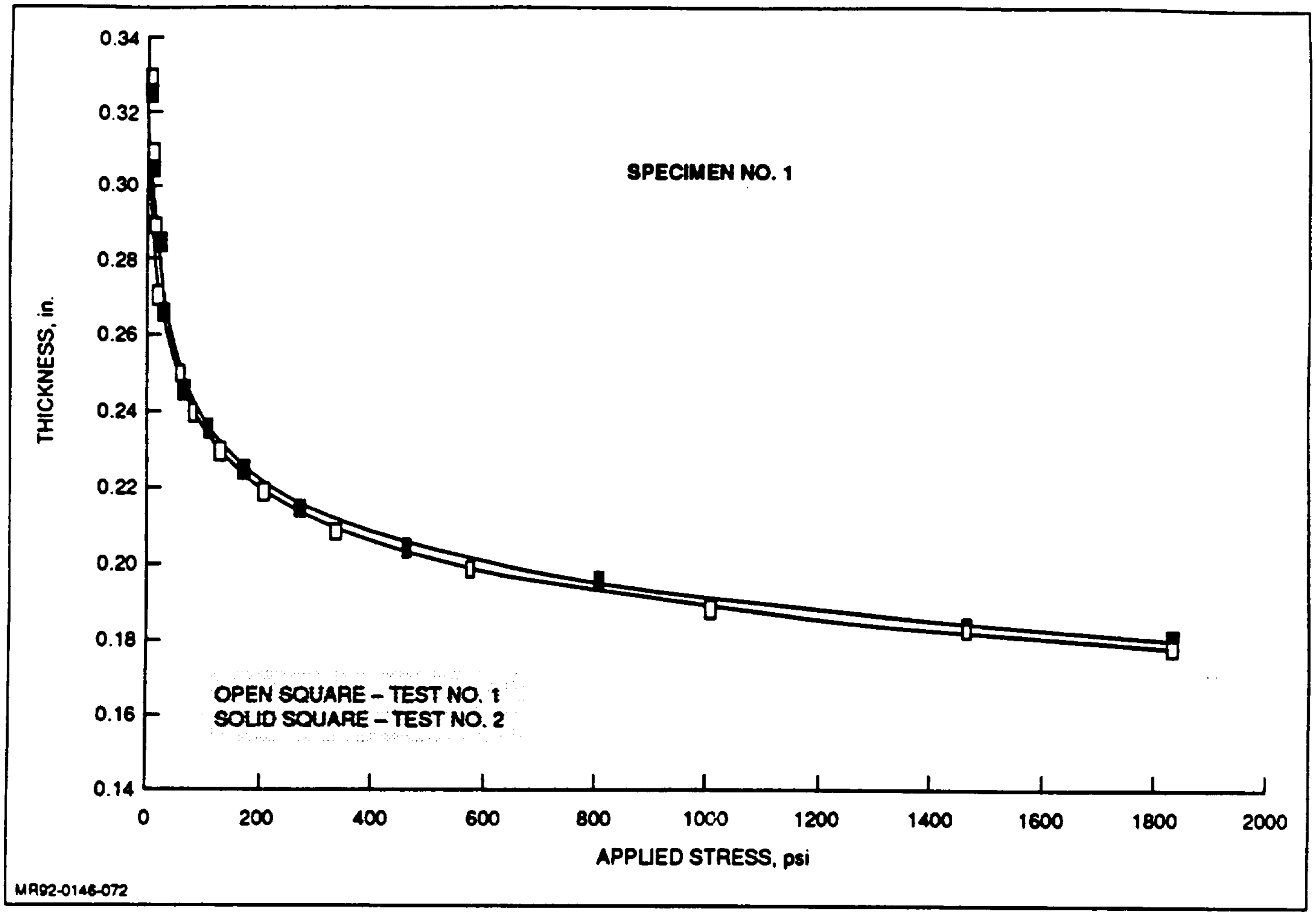

Fig. 32 IM7 "Y"– Spar Preforms Dry Compaction

Visual inspection indicated several large dry areas in both the webs of each part and in the flanges. There was a generally poor appearance throughout both parts, with the stitches protruding from the surfaces of the parts, indicating that the stitches' extra thickness (bulk) contributed greatly to Compositek's inability to fully close the tool. Ultrasonic NDI of the two spars confirmed our visual analysis, indicating large void areas where dryness was observed. Additionally, because the preforms' flanges did not have sufficient width in some areas, the parts were received with obvious trimming in evidence. Consequently, it was not possible to ascertain whether their edges were resin rich, a common problem with RTM-processed parts.

Based on the visual and NDI results, no further effort was expended on the "Y"-spars. (See later discussion under D19B8220-15 for a related RTM effort by Compositek on a knitted/stitched preform.)

4.2.3 D19B8220-11 Replacement "Y"-Spar Fabrication (RFI)

As mentioned earlier, in an effort to prove to Grumman's satisfaction that they are capable of providing a preform to our engineering requirements, TTI agreed to fabricate a replacement -11 carcass. They wove it on the same Jacquard loom on which the original carcasses were made. However, this carcass was woven with the proper number of picks per inch, based on the specified architecture.

The carcass was then shipped to Ketema for stitching of the ±45-deg. plies. The completed preform was then sent back to TTI for the PVA serving to be boiled off prior to further processing. The completed preform is shown in Fig. 33. After inspection, it was sent to Compositek Corporation for processing via RFI and Autocomp. The decision to process this preform by RFI, rather than by RTM as originally planned, was based on the extremely good results achieved by Compositek on the -15 spars that were RFI-processed. (See further discussion of this effort below.)

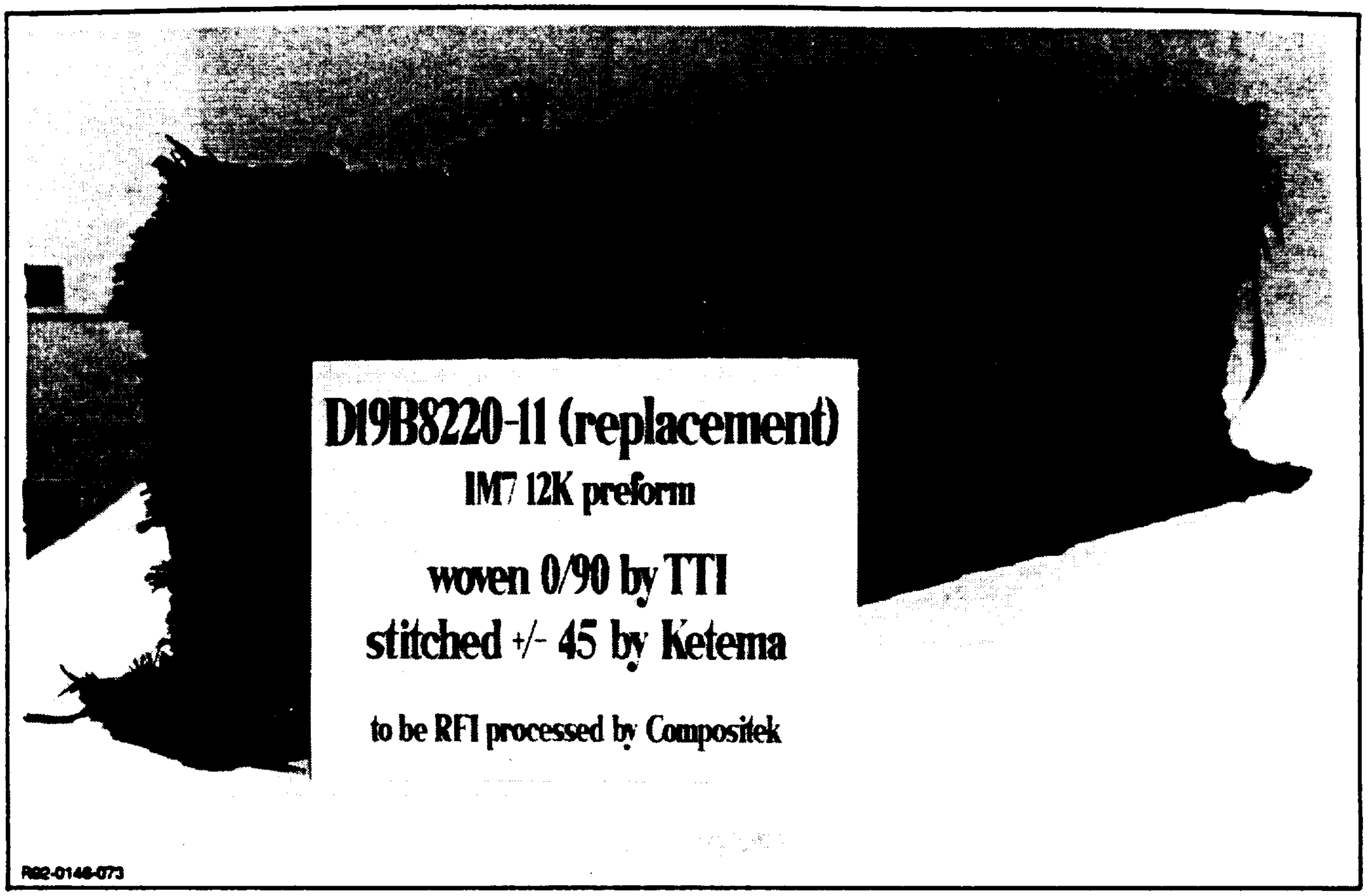

Fig. 33 D19B8220-11 Replacement Preform Prior to Processing

Compositek successfully RFI-impregnated and autoclave-processed the -11 replacement "Y"-spar using Hercules 3501-6 epoxy film resin. As with the -15 "Y"-spar, rather than Autocomp consolidating the part, it was conventionally consolidated in an autoclave. (See Subsection 4.2.6.2 for a discussion of the RFI-processed-15 "Y"-spars and background information regarding the processing decision.)

An initial visual inspection of the part indicated some surface porosity throughout the spar. Ultrasonic inspection confirmed these porous areas. However, despite these imperfections, it was decided to subject the part to four-point beam bending, for comparison to the previous spars' results in these tests.

Figure 34 provides a comparison of the target and actual part dimensions of the spar. As with the RFI-processed -15 spars (see Fig. 51), both the web and the flanges are generally thicker than targeted. It is still not clear whether this oversizing is due to the tool itself or is process-dependent.

DIM. LTR	TARGET, In.	FINAL, In.
A	0.135	0.171
B1	0.102	0.108
B2	0.102	0.117
C	2.50	2.47
D1	0.102	0.126
D2	0.102	0.123
E1	1.25	0.86
E2	1.25	0.88
F	10.59	10.59
G	3.40	3.43
H1	0.102	0.116
H2	0.102	0.114

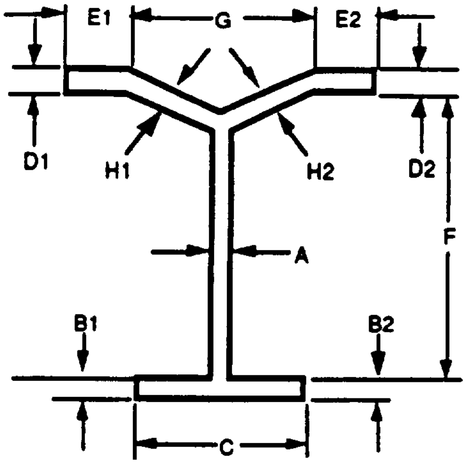

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Fig. 34 Woven/Stitched IM7 12K/3501-6 -11 Replacement "Y"-Spar (RFI Processed) Target and Final Part Dimensions

As with the other spars, this part was trimmed to length for testing under four-point beam bending. Figure 35 shows the completed "Y"-spar with the caps installed and the holes drilled to support this test. Results are presented elsewhere in this report. The excess material from each of the spars was sectioned into physical properties coupons. The average values for the "Y"-flanges were: 53.2% fiber volume, 45.0% resin volume, and 1.8% void. The average values for the "Y"-web were: 56.1% fiber volume, 41.1% resin volume, and 2.8% void. The weight of the 35-in. long "Y"-spar tested is 5.04 lb.

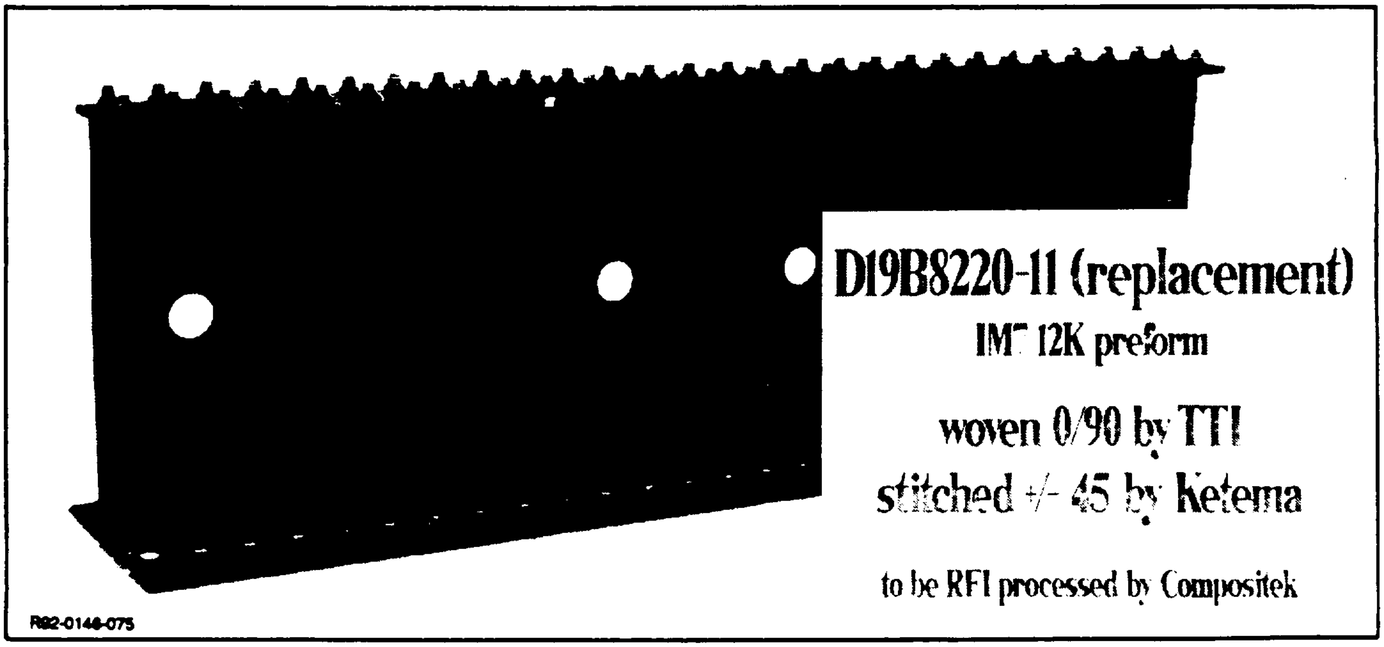

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Fig. 35 Completed D19B8220-11 Replacement "Y"-Spar With Caps Installed in Preparation for Four-Point Beam Bending Test

4.2.4 D19B8220-13 "Y"-Spar Fabrication

This effort involved the consolidation (thermoforming) of three woven/stitched AS4 6K/PEEK 150g "Y"-spars. The required configuration of these spars is shown in Fig. 24, the Grumman Engineering Drawing. The PEEK resin in these preforms was commingled in the proper proportion with the AS4 graphite fiber yarns prior to weaving and stitching. As with the other subtasks, several subcontractors were involved in this fabrication effort, as discussed below.

The 0-deg/90-deg carcasses were woven by TTI in the same setup as that of the D19B8220-11 carcasses. This reduced the cost of the preforms by minimizing the setups involved with essentially an equivalent structure. The ±45-deg ply material was then located on the outside faces of both the webs and flanges of the completed carcasses by TTI, and semiautomatically stitched in place by Sewing Machine Exchange (SMX), Chicago, IL, using Toray T900-1000A fiber. The completed preforms were then shipped back to TTI for inspection, and then to Grumman for quality checks.

Since the 0/90-deg carcasses were woven in the same setup as that of the -11 carcasses, the same errors occurred in the -13 carcasses. That is, both the web heights and the thicknesses were incorrect.

Concurrent with the preform fabrication efforts of TTI and SMX, Coast Composite Corp., Irvine, CA, was machining a set of matched monolithic graphite tools for Grumman's consolidation of the -13 preforms. Monolithic graphite was chosen for the tooling, based on several advantages over more conventional materials. These are:

- Coefficient of Thermal Expansion (CTE) near that of the part
- Fairly high thermal conductivity
- Excellent surface finishes possible for good part finish and ease of release
- Relatively low cost.

The tool consists of four machined details: two matching left and right halves for the web, and top and bottom details for the flanges. Three of the tool's details are pictured in Fig. 36. Due to the incorrect weaving of the carcasses as noted above, the tooling, as received, required modification. Figure 37 shows the "T"-flange of a preform protruding above the tool because its web is too long.

As a result of the improperly sized preforms, the tool's two largest details were sent back to Coast Composites for rework, based on the sketch shown in Fig. 38. The two details were modified by machining the "T"-end of each flat, bonding an oversize billet of graphite onto each and then remachining them to the new, larger web height dimension (10.700 in.) per the drawing.

When the modified monolithic graphite tools were received by Grumman, the three commingled "Y"-spar preforms were consolidated, with each successive effort's processing based on examination of the previous run(s) in an iterative fashion. Figure 39 shows a preform loaded into the monolithic graphite tool prior to bagging, while Fig. 40 shows the setup located in the autoclave prior to consolidation. Figure 41 is the consolidated, but untrimmed, "Y"-spar, and Fig. 42 is the part after trimming.

All three completed spars were ultrasonically inspected for voids. Both the first and third spars processed showed several minor void areas, particularly in the flanges, while the second spar tested as almost void-free, with only small areas of questionable quality in the angular sections of the "Y"-flanges. Based on these results, all further testing was done on the second "Y"-spar only.

Physical property analysis yielded an average fiber volume in the spar of 56.1%, an average resin volume of 42.8% and 1.1% voids. Interlaminar shear strength of the spar, at room temperature dry conditions, was 11.0 ksi in the web and 10.4 ksi in the flanges.

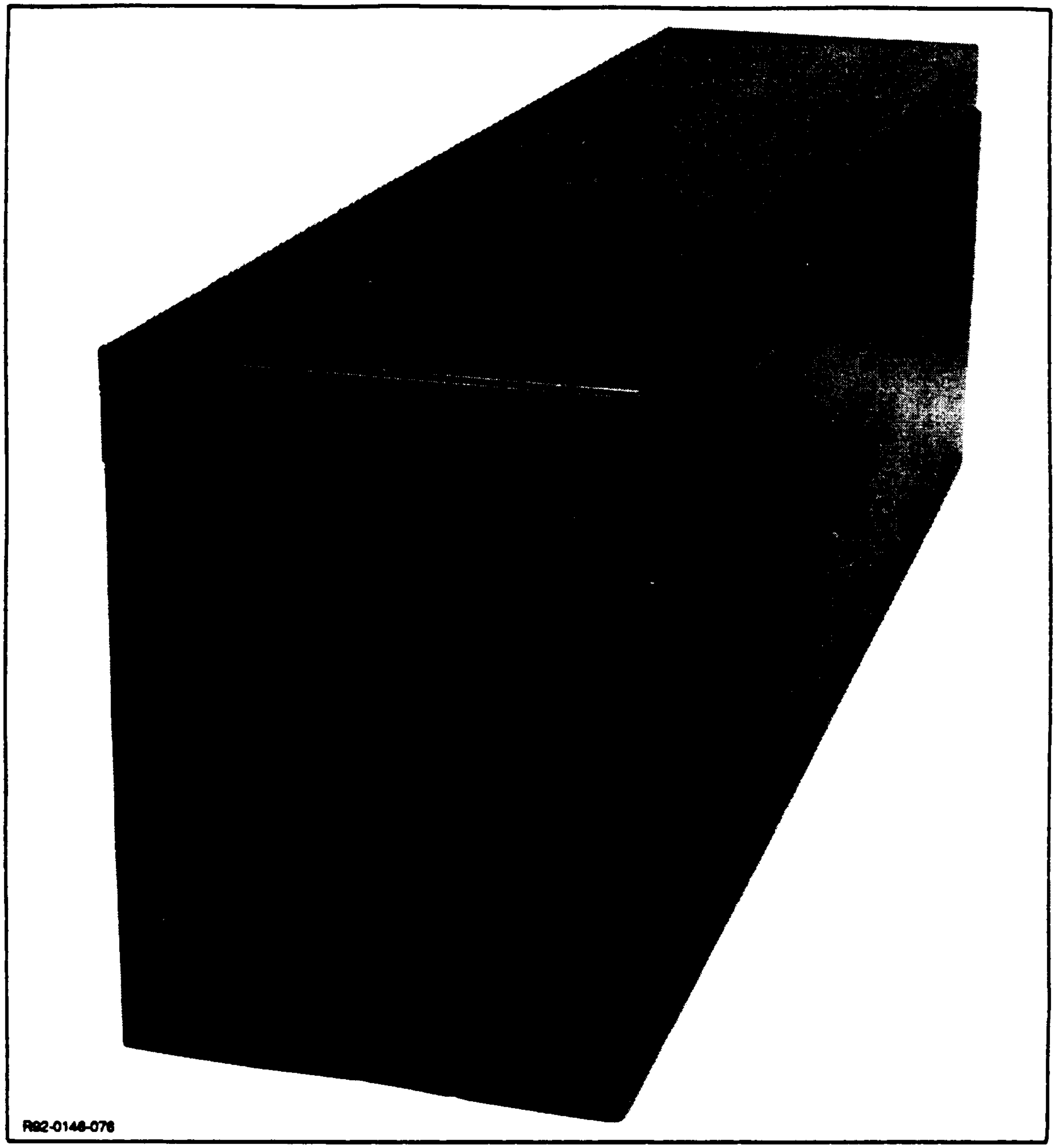

Fig. 36 Matched Monolithic Graphite Tooling for D19B8220-13 "Y"-Spars

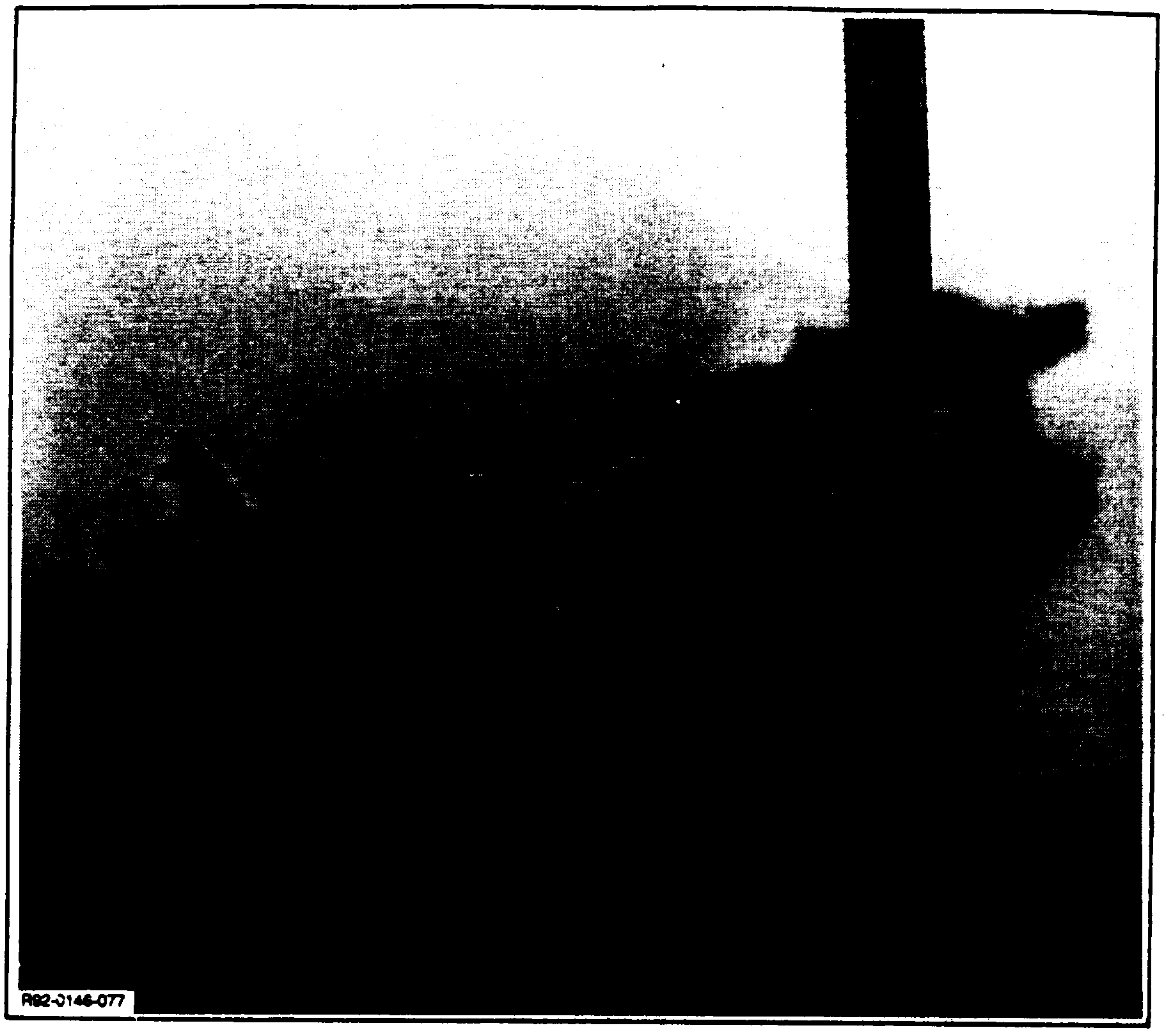

Fig. 37 Preform's "T"-Flange Protruding Above As-Designed Monolithic Graphite Tool

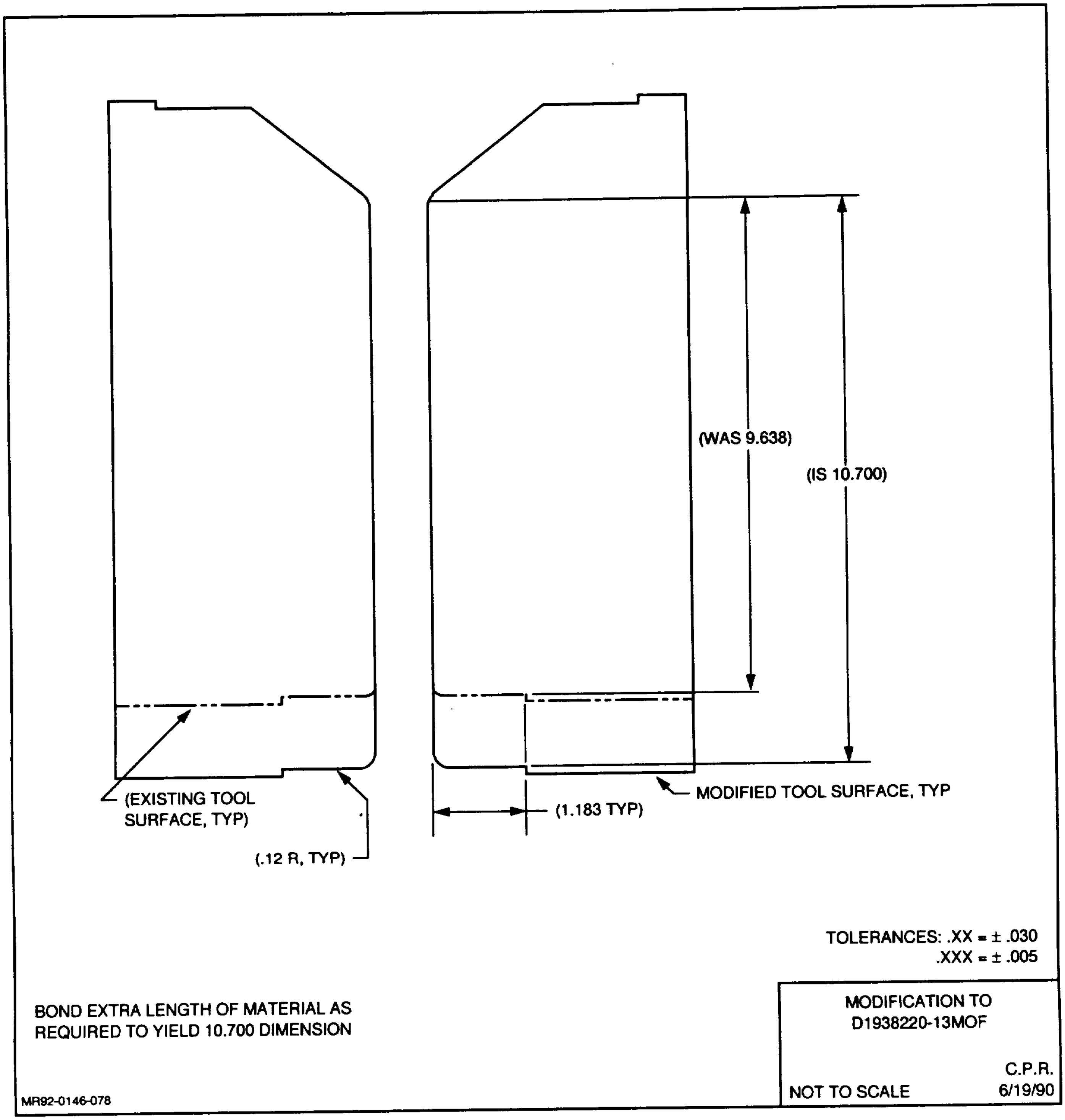

Fig. 38 Sketch Detailing Modification to Monolithic Graphite Tools

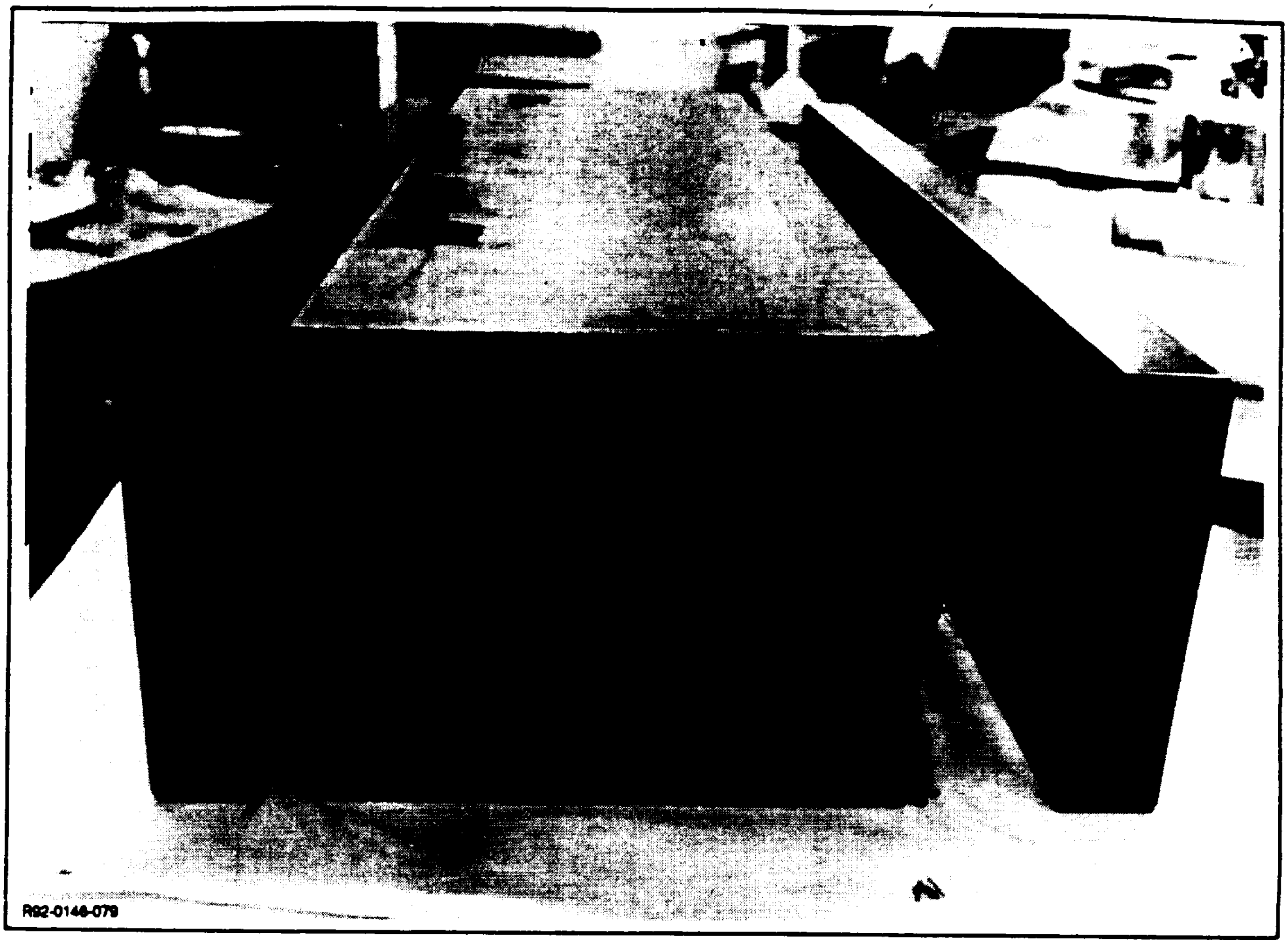

Fig. 39 D19B8220-13 Preform (Trimmed) Located in Graphite Mold Form

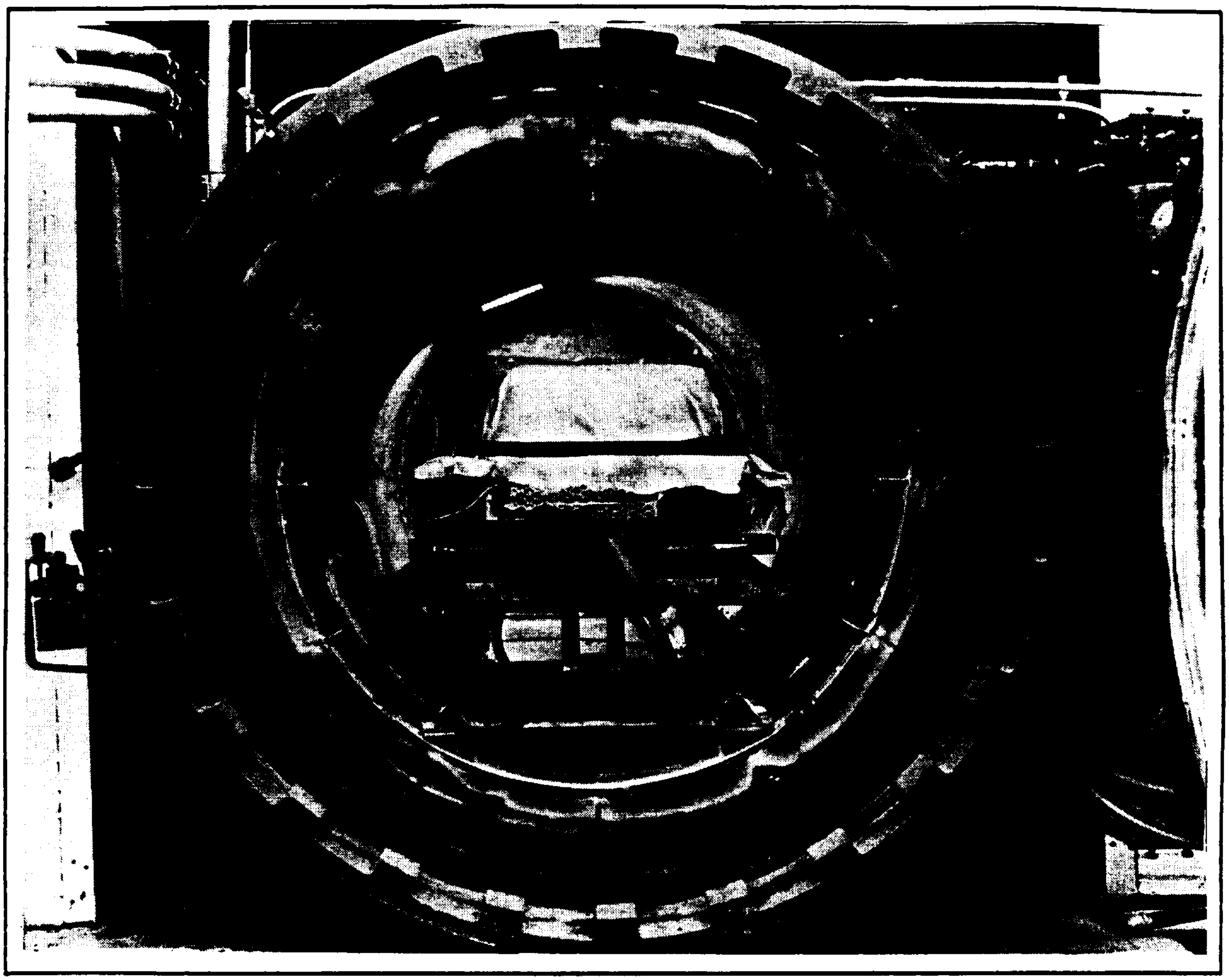

Fig. 40   D19B8220-13 In Autoclave Prior to Being Consolidated

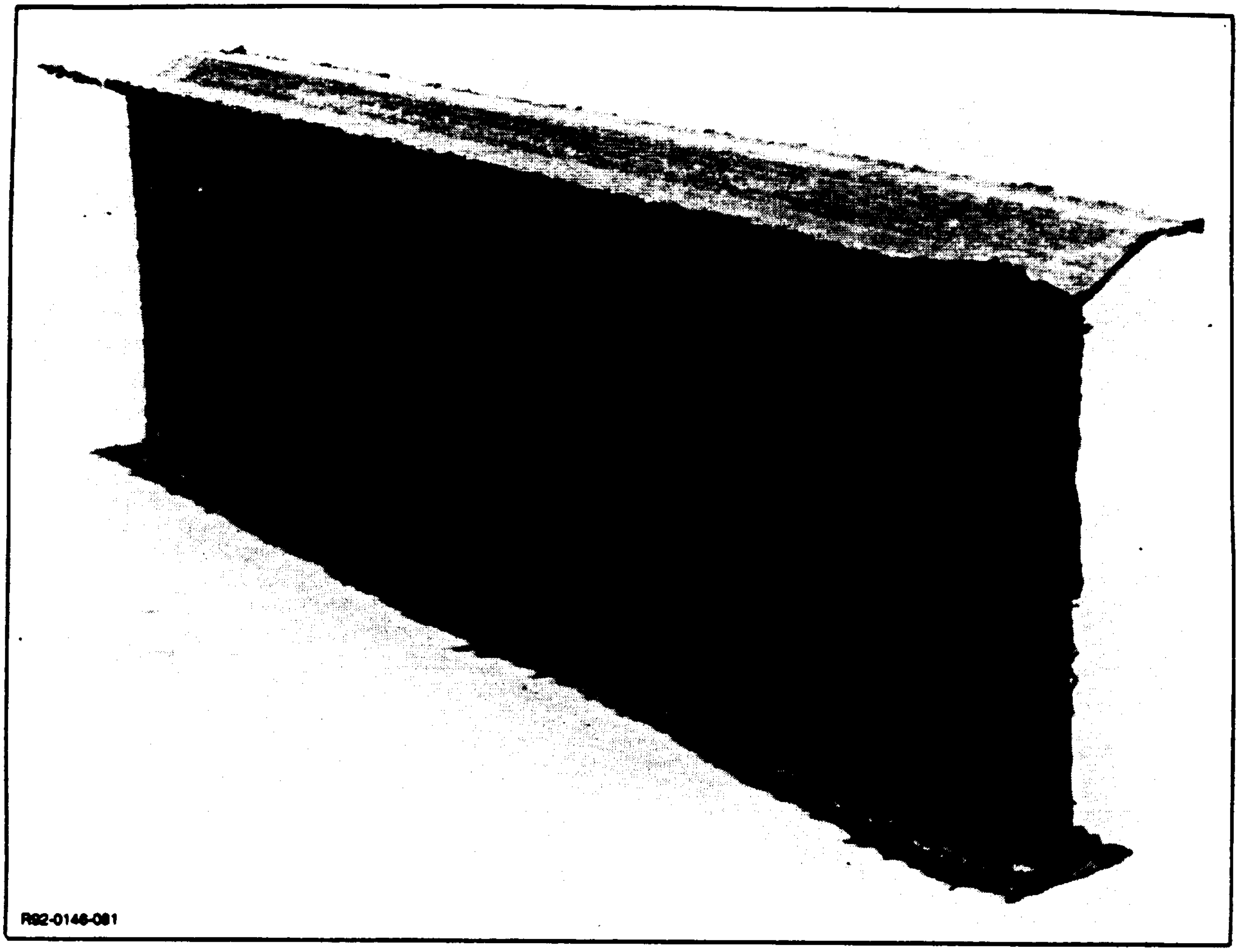
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Fig. 41 Consolidated D19B8220-13 "Y"-Spar Prior to Trimming

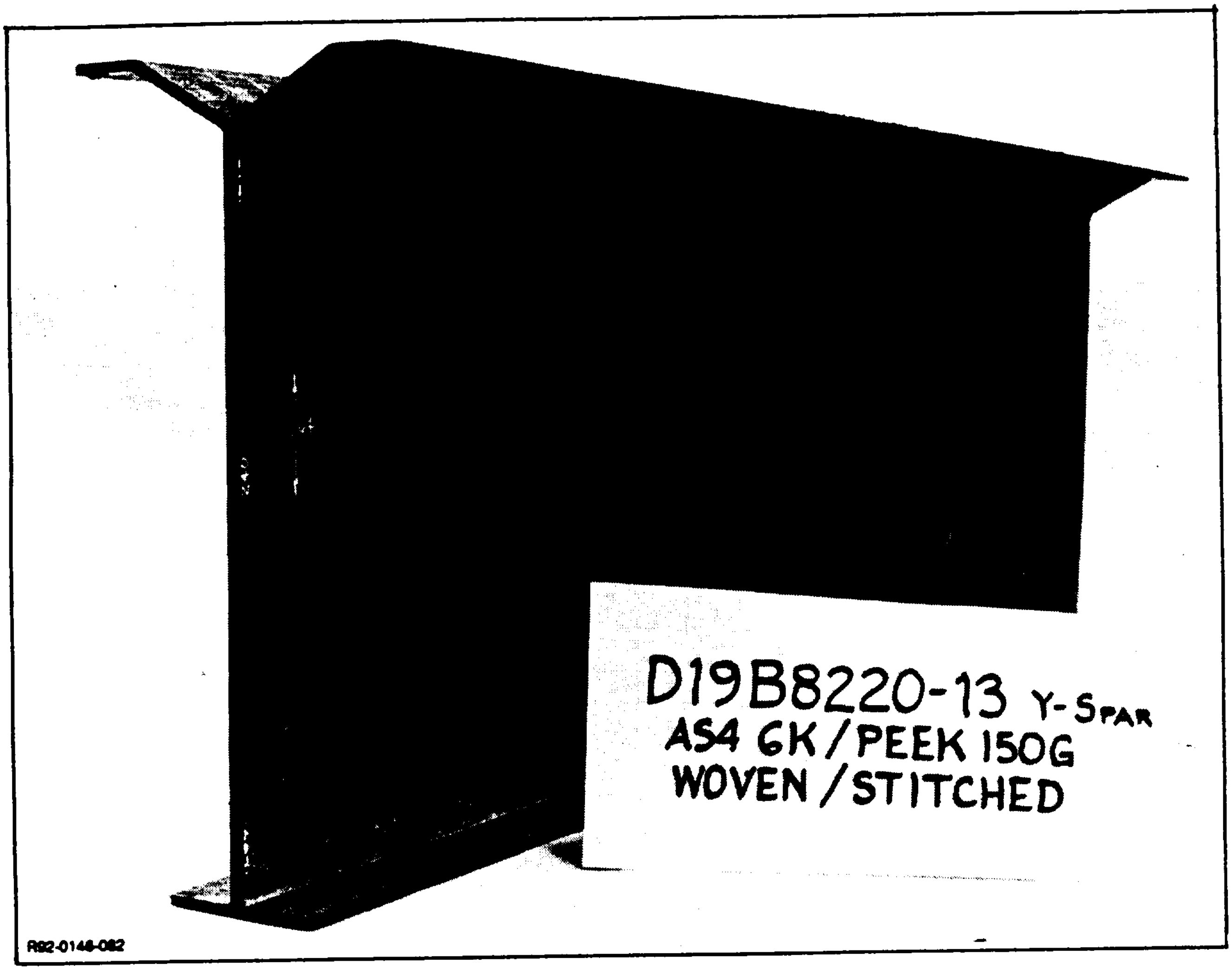
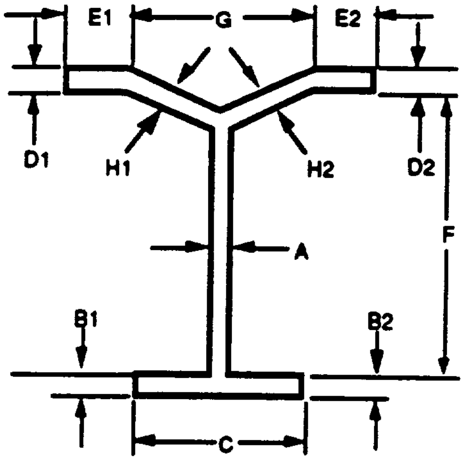


Fig. 42 D19B8220-13 "Y"-Spar After Trimming

Figure 43 presents a comparison of the three spars' target, preform, and final part dimensions. (The target dimensions are adjusted for the oversize and overthickness conditions of the preforms.) Also provided are the percentage of consolidation for each of the "Y"-spars. This is a measure of how the bulk factor of each of the preforms related to each finished part's final thicknesses. Ideally, the consolidation percentages should be fairly closely matched within each part and among the three parts.

Again the second spar, S/N 2, provided the best results dimensionally. With the exception of the web thickness (letter A) of 0.240 in. and a consolidation percentage of 47.6, the other thickness dimensions have consolidation percentages between 56.3 and 62.0. This is the tightest range of the three spars, and is reflected in the better NDI results mentioned earlier. The raw dimensions of spar S/N 2 also are the most consistent among the three spars. Both the angular and horizontal areas of the "Y"-flange (for example, letters D1, D2, H1, and H2) have thicknesses ranging from 0.142 to 0.160 in., and although the thicknesses of the two legs of the "T"-flange (letters B1 and B2) are somewhat less, at 0.123 and 0.119 in. respectively, this condition exists in all the spars. It is a reflection of the greater thickness of all the preforms in the "Y"-end.



DIM.	TARGET DIM. In.	Y-SPAR S/N-1			Y-SPAR S/N-2			Y-SPAR S/N-3		
		PRE-FORM, In.	CONS. SPAR, In.	PERCENT CONS, %	PRE-FORM, In.	CONS. SPAR, In.	PERCENT CONS, %	PRE-FORM, In.	CONS. SPAR, In.	PERCENT CONS, %
A	0.215	0.463	0.242	47.7	0.458	0.240	47.6	0.438	0.238	45.7
B1	0.151	0.381	0.134	64.8	0.315	0.123	61.0	0.334	0.126	62.3
B2	0.151	0.350	0.127	63.7	0.313	0.119	62.0	0.375	0.126	66.4
C	2.50	2.74	2.50	N/A	2.67	2.50	N/A	2.36	2.40	N/A
D1	0.151	0.366	0.156	58.2	0.366	0.160	56.3	0.357	0.157	56.0
D2	0.151	0.397	0.141	64.5	0.352	0.142	59.7	0.382	0.143	62.6
E1	1.25	–	0.90	–	–	0.70	–	–	0.70	–
E2	1.25	–	1.00	–	–	0.90	–	–	0.70	–
F	11.65	–	11.65	–	–	11.65	–	–	11.61	–
G	3.40	–	3.34	–	–	3.40	–	–	3.36	–
H1	0.151	0.366	0.170	53.6	0.366	0.156	57.4	0.357	0.156	56.3
H2	0.151	0.397	0.158	60.2	0.352	0.153	56.5	0.382	0.152	60.2

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Fig. 43 Comparison of D19B8220-13 S/Ns 1, 2, and 3 Target, Preform, and Final Part Dimensions

With regard to the spars' web thicknesses (letter A) of 0.242, 0.240, and 0.238 in., respectively, and their correspondingly low consolidation percentages, it is apparent that the bulkiness of the preforms' webs, combined with the large area of web, made it impossible to compact these areas down to the target value of 0.215 in. From these results, it can safely be assumed that, given a properly sized preform with a web target thickness of 0.135 in., this dimension would also have been unachievable.

The second -13 "Y"-spar was destructively tested in four-point beam bending; results of this testing are reported elsewhere in this report.

4.2.5 D19B8220-13 Replacement "Y"-Spar Fabrication

As with the -11 preform, in an effort to prove to Grumman that they can provide a preform to our Engineering requirements, TTI agreed to fabricate a replacement -13 carcass. This was woven with the proper number of picks per inch, based on the specified architecture. However, as the weaving progressed, it became obvious that there would not be enough AS4 fabric to complete the ±45-deg plies of the preform. Consequently, due to the program's tight schedule, Grumman supplied TTI with some material that became available from another program. The material, BASF HFGRPK007 unidirectional fabric, is a 3K AS4/PEEK that is approximately half the density of the original material intended for this part. Therefore, two plies of the replacement material located for each ply of original material would create an equivalent structure. Figure 44 is a closeup of the completed preform, clearly showing where the BASF material was added in lieu of the originally specified fabric.

The carcass was then shipped to Ketema for stitching on the ±45-deg plies. The completed preform was then shipped back to TTI for quality assurance checks, prior to further processing. After inspection, it was sent to Grumman for consolidation on the monolithic graphite tooling used for the oversize/overweight preforms. The completed preform is shown in Fig. 45.

In order to accommodate the properly sized preform, the tool's two large details (see Fig. 46) were sent back to Coast Composites for remachining down to their original configuration. This effort was completed without incident, and the tools were shipped back to Grumman in March. This last commingled "Y"-spar was not processed because it arrived far too late in the program to meet schedule constraints and we had already processed successfully the three previous oversize preforms.

4.2.6 D19B8220-15 "Y" Spar Fabrication

The original plan for this subtask was for Compositek Corporation to infuse a dry knitted/stitched G40-800 graphite preform made by them with the Toray 3900-2 resin system via their proprietary process known as Resin Film Infusion (RFI). In this process, resin in film form is positioned within the fiber preform as the preform is being constructed. The fiber and resin are then heated in a vacuum chamber, thus impregnating the preform by gravity and capillary wetting. During the infusion, the vacuum is pulsed to remove entrapped air and volatiles from the resin.

The impregnated preform was then to be processed by Compositek using their Autocomp technique. This proprietary procedure combines aspects of compression molding and autoclave molding in one process. The preform is installed in an integrally heated, matched mold and the setup is located inside a reusable vacuum bag that is contained within the Autocomp pressure vessel. Vacuum is then drawn on the part while the tool is heated. At the proper temperature for the particular resin system, vacuum is shut down and fluid pressure applied to fully close the tool and complete the part's processing.

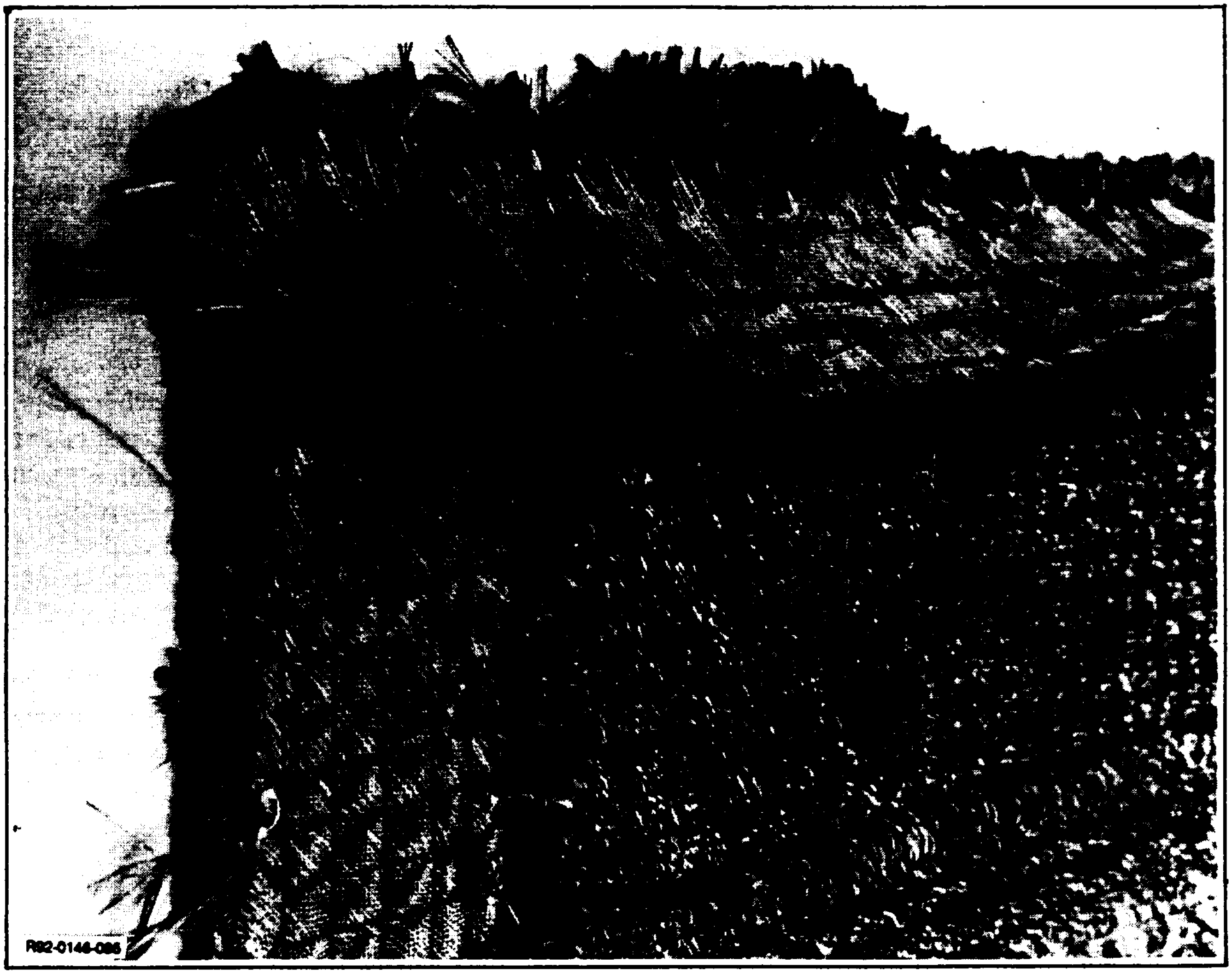


Fig. 44 Close-up of BASF Replacement Material on D19B8220-13 Preform

As the program progressed, several difficulties arose that required some deviations from the original plan. The first involved the availability of Toray 3900-2 resin for use in the RFI/Autocomp effort. Due to ongoing patent infringement litigation between the Toray Marketing and Sales (American) Company and Boeing, Toray currently cannot release the material for sale on the open market. Consequently, Grumman and Compositek held technical discussions to determine the feasibility of using an alternative resin system for this subtask of the program. This question dealt not only with whether or not a particular candidate system would fulfill the Engineering requirements, but also whether it was available in film form in order to be compatible with the RFI process. Initial investigation centered on the Shell Epon DPL 862 resin system. After it became apparent that the bulk properties of this system were incompatible with RFI, the BP chemicals E707 GD resin system was investigated for use. Ultimately, however, Hercules 3501-6 epoxy film resin was actually chosen for the processing of the last two knitted/stitched "Y"-spars.

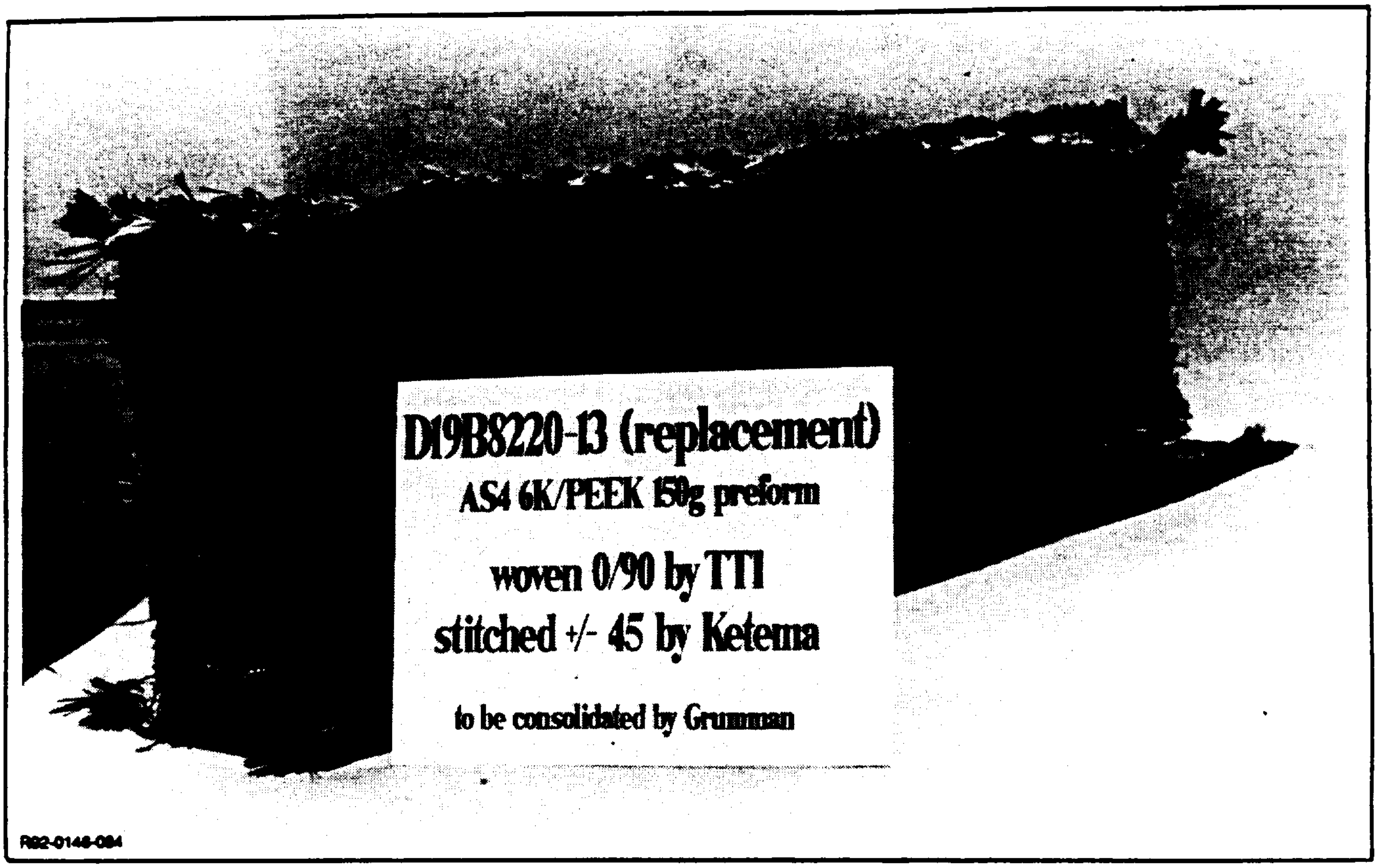


Fig. 45 D19B8220-13 Replacement Preform Prior to Processing

During fabrication of the -15 knitted/stitched preforms, Compositek erred in the percentages of each of the orientation directions. The Grumman-specified architecture is given below:

Flanges:	0 deg	7%
	±45 deg	51%
	90 deg	42%
Web:	0 deg	10%
	± 45 deg	58%
	90 deg.	32%

Due to the error, the "Y"-spar architecture provided by Compositek is:

Flanges:	0 deg	6%
	±45 deg	55%
	90 deg	39%
Web:	0 deg	9%
	±45 deg	62%
	90 deg	29%

Grumman project Engineering personnel reviewed the "new" architecture and determined that the impact on the resultant parts would be minimal and that the preforms were acceptable as is.

Another potential pitfall that surfaced at about this time was the fact that Shell, the parent organization of Compositek, had only recently acquired the Xerkon Corporation along with their equipment and proprietary processes (i.e., RFI and Autocomp). In moving from Minneapolis, MN, where Xerkon had

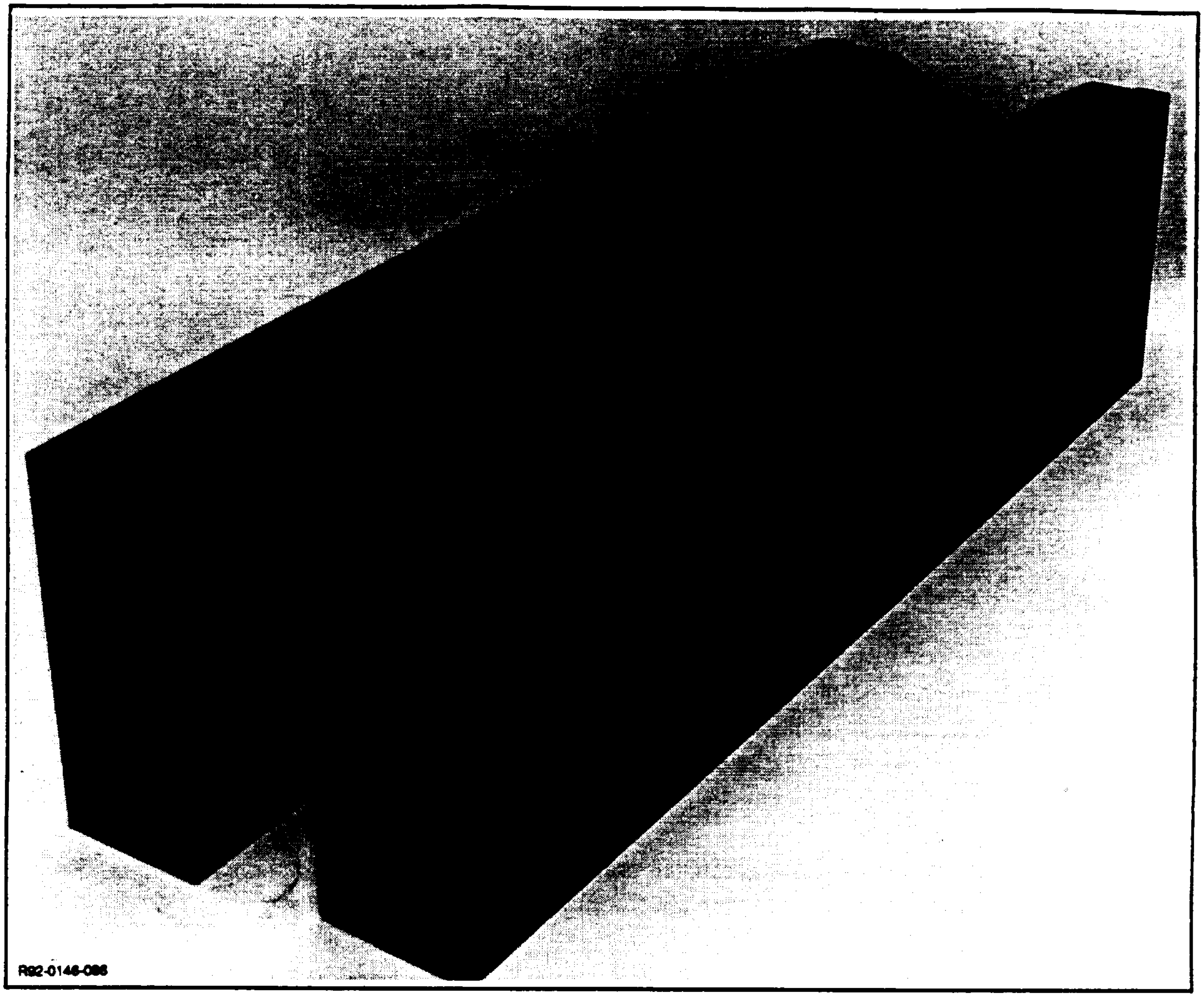


Fig. 46 Two Monolithic Graphite Details That Required Remachining

been located, to Brea, CA, Compositek's home, the equipment had not yet been uncrated and therefore not yet used in the new location. Additionally, none of the former Xerkon employees familiar with the RFI/Autocomp processes relocated to California, and Compositek's principal engineer supporting Grumman's subcontracted work left the company suddenly. Hence, there was some concern on Compositek's part regarding their ability to technically support the two processes within the constraints of the program's schedule.

As a result of the above considerations, a program decision was made for Compositek to RTM-process one of their knitted/stitched preforms, while RFI/Autocomp processing the remaining two as soon as possible. Each of these independent efforts is discussed separately below.

4.2.6.1 RTM-Processed D19B8220-15 "Y"-Spar – From a technical standpoint, this RTM effort provided a direct comparison between the woven/stitched -11 and the knitted/stitched -15 preforms in the resulting RTM-processed parts. Therefore, the resin system chosen for this knitted/stitched preform's impregnation was Dow Tactix 123/H41, the same resin used in the -11 woven/stitched preforms RTM processing. Also, the preform was processed in the same RTM tool that Compositek had used to impregnate the two -11 preforms (with the temporary shims removed for this correctly sized preform).

Overall, this operation produced good results, yielding a part with only minimal resin richness along its periphery in localized areas. The completed "Y"-spar is shown in Fig. 47. The only major anomalies exhibited in the part were localized dry areas in the angular segments of the "Y"-flange. Figure 48 provides a close-up view of this condition on the worst end. These resulted from a blown "O"-ring seal in the "Y"-flange during processing. Results of the ultrasonic inspection of this spar confirmed that these areas were unsatisfactory. However, the remainder of the part was predominantly free of sonic indications.

A preliminary dimensional analysis of the RTM-processed "Y"-spar provided the results shown in Fig. 49. Again, overall results are excellent. There are two potential causes for concern, however. The first is the somewhat thin angular faces of the "Y"-end, dimensions H1 and H2. This condition is undoubtedly due to the previously discussed seal failure.

The other concern is the inconsistency in the thickness of the web, dimension A. Although shown in Fig. 49 as only a 0.015 in. deviation from the target value, 0.150 in. vs 0.135 in., the difference is in fact the result of an increase in the web thickness toward the spar's center. The ends of the web measure 0.138-in. and 0.142-in. thick, while the center measures 0.170 in. It is not clear whether this condition was caused by a tooling problem or localized thickness (bulkiness) in the preform, or is somehow related to the seal failure experienced during resin injection. Physical property analysis yielded an average fiber volume of 52.5% and an average resin volume of 47.4%. The spar was then destructively tested in four-point beam bending; results of this testing are reported in Section 5.

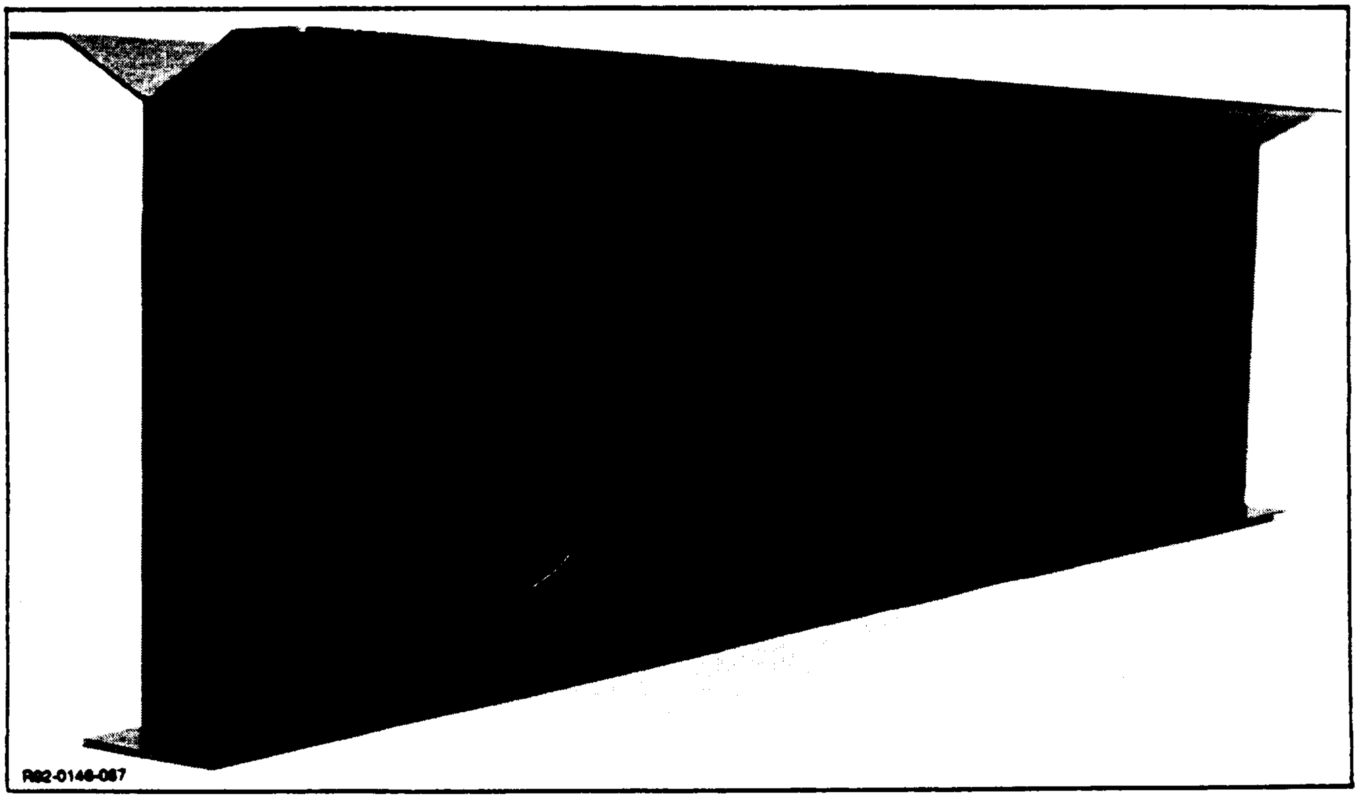


Fig. 47 Completed D19B8220-15 (RTM) "Y"-Spar No. 1

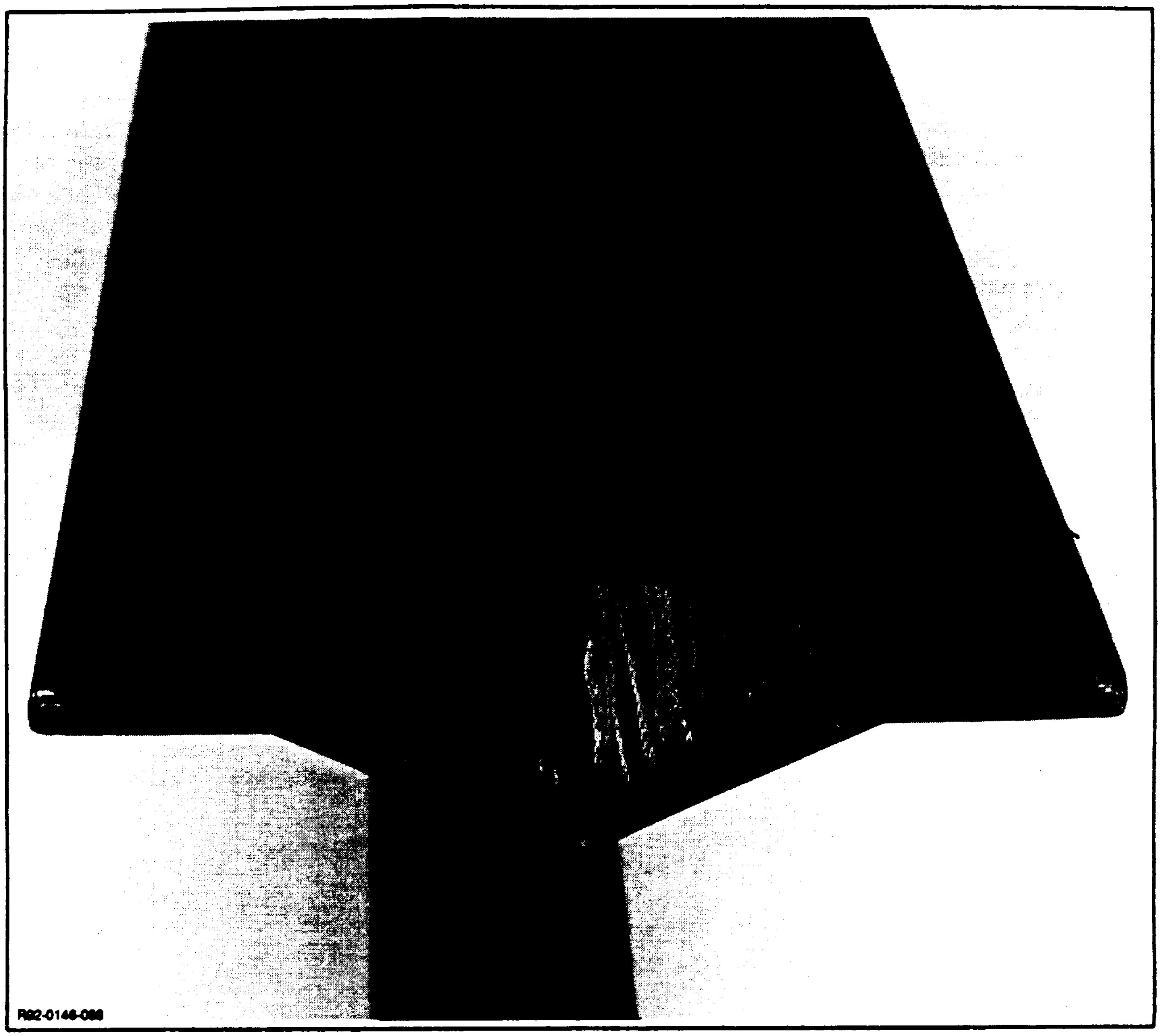
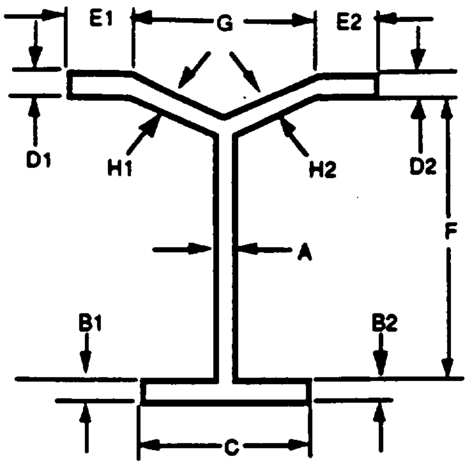


Fig. 48 Close-up of Worst Dry Area of D19B8220-15 (RTM) No. 1 Due to Failure of "O"-Ring Seal During Injection

4.2.6.2 RFI-Processed D19B8220-15 "Y"-Spars – Compositek successfully RFI-impregnated and autoclave-processed the remaining two knitted/stitched preforms using Hercules 3501-6 resin. In addition, they fabricated a fourth knitted/stitched spar via RFI/autoclave processing. The only processing deviation is that, rather than Autocomp-consolidating the three spars, they were conventionally consolidated in an autoclave. This was apparently due to setup problems with Compositek's Autocomp pressure vessel and related equipment. (To avoid confusion among the different -15 "Y"-spars, the three RFI-processed parts will be referred to as RFI Serial No. (S/N) 1, 2, and 3, respectively, while the previously RTM-processed -15 spar will be referred to as RTM S/N 1.)



DIM LTR	TARGET, in.	FINAL, in.
A	0.135	0.150
B1	0.102	0.103
B2	0.102	0.104
C	2.50	2.50
D1	0.102	0.114
D2	0.102	0.112
E1	1.25	1.24
E2	1.25	1.22
F	10.59	10.58
G	3.40	3.46
H1	0.102	0.089
H2	0.102	0.091

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Fig. 49 Knitted/Stitched G40-800/Dow Tactix 123/H41 "Y"-Spar S/N1 (RTM Processed) Target and Final Dimensionss

From an initial visual standpoint, RFI S/N 1 was of poor appearance overall, with large obviously dry areas throughout the spar. On the other hand, both RFI S/N 2 and 3 looked quite good, with no apparent bad areas. As a result, it was decided to further analyze only RFI S/N 2 and 3; no further examinations or analyses were made of RFI S/N 1. Figure 50 shows the completed "Y"-spar D19B8220-15 RFI S/N 2.

Both RFI S/N 2 and 3 were ultrasonically inspected via "C" scan, with results indicating that RFI S/N 2 was void-free and that RFI S/N 3 contained only a small void in one horizontal leg of the "Y"-flange. Figure 51 provides a comparison of the target and part dimensions of both RFI S/N 2 and 3. It is apparent that although the spars are dimensionally consistent, they are both thicker than as targeted (except for dimensions H1 and H2, the angular component of the "Y"-flange, which in both parts is slightly undersize.) Whether this general oversizing is due to the tool itself or is process-dependent is not known at this time.

Both RFI S/N 2 and 3 were trimmed to length and RFI S/N 3 was subjected to destructive testing under four-point beam bending. The excess material from each of the spars was sectioned into physical properties coupons. Results of these analyses are: S/N 2 fiber volume 52.8 percent, resin volume 46.0 percent; and S/N 3 fiber volume 57.3 percent, resin volume 41.2 percent.

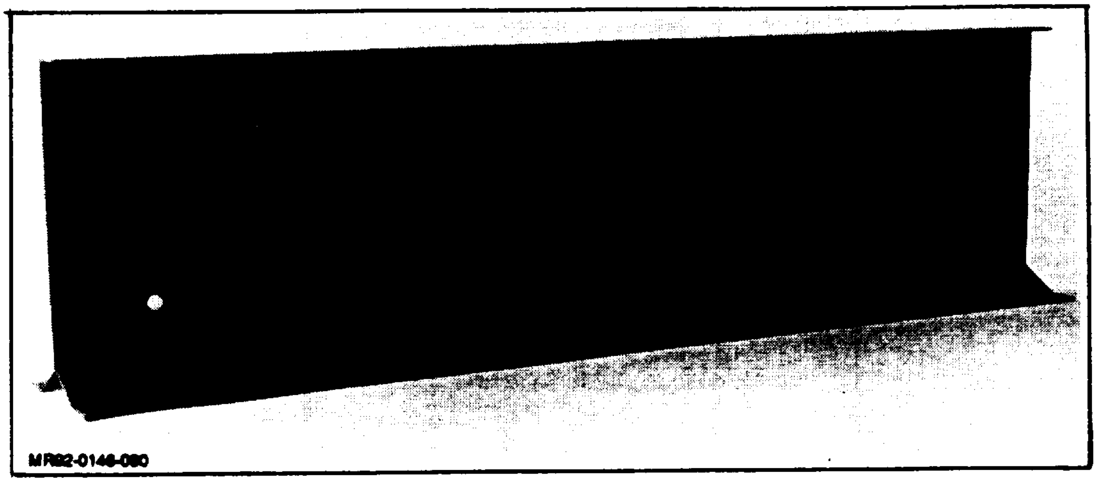
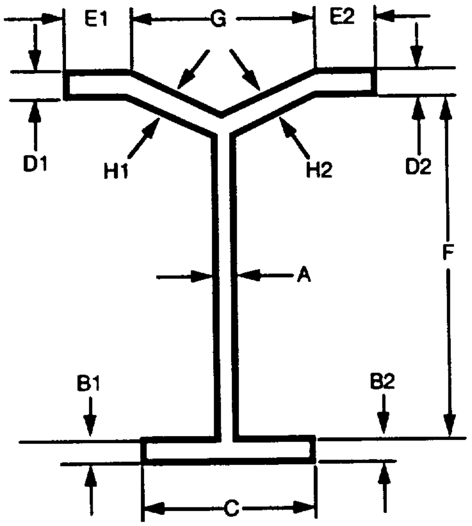


Fig. 50 Finished D19B8220-15 RFI S/N 2 G40-800/3501-6 "Y"-Spar



DIM LTR	TARGET, in.	FINAL DIMENSION, in.	
		RFI S/N 2	RFI S/N 3
A	0.135	0.158	0.153
B1	0.102	0.116	0.111
B2	0.102	0.113	0.114
C	2.500	2.74	2.74
D1	0.102	0.121	0.116
D2	0.102	0.116	0.123
E1	1.25	1.340	1.36
E2	1.25	1.35	1.34
F	10.59	10.58	10.59
G	3.40	3.50	3.46
H1	0.102	0.096	0.094
H2	0.102	0.095	0.097

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Fig. 51 Comparison of D19B8220-15 (RFI) S/Ns 2 and 3 Target and Final Part Dimensions

4.3 MANUFACTURING COSTS

Manufacturing costs to produce the various "Y"-spars shown in Fig. 24, the Engineering Drawing, were estimated for each of the three material form/processing combinations. These approaches, as discussed earlier, are:

- Woven/stitched IM7 preform impregnated with Dow Tactix 123/H41 resin system using RTM procedures (D19B8220-11)
- Woven/stitched AS4/commingled PEEK preform thermoformed (consolidated) via autoclave/ vacuum bag procedures (D19B8220-13)
- Knitted/stitched G40-800 preform impregnated with Hercules 3501-6 resin system via Resin Film Infusion (RFI) and then autoclave-processed (D19B8220-15).

Additionally, costs were estimated for the fourth type of "Y"-spar: the woven/stitched preform that was impregnated via RFI and then autoclave processed (D19B8220-11 replacement).

Comparative manufacturing costs were based on actual costs for tooling (nonrecurring costs), and estimates for labor and materials (recurring costs). These costs comparisons were developed for the fabrication of one "Y"-spar of each type, based on a production run of 100 units.

4.3.1 Tooling Costs

Tooling for each of the three processes was designed and fabricated by outside subcontractors, each of whom specializes in the particular materials and processes involved in the tools. Actual tool fabrication costs are presented below, for each of the three tools:

- Aluminum RTM tool for D19B8220-11 "Y"-spar: $18,932.00
- Monolithic graphite tool for D19B8220-13 "Y"-spar: $10,869.00,
- Aluminum RFI/autoclave tool for D19B8220-15 and -11 replacement "Y"-spar: $20,000.00.

In order to generate the prorated hours to reflect the design and fabrication cost of the 100-unit production run scenario, each of the above dollar figures was converted to an equivalent number of hours by dividing by a labor rate of $100.00 per hour. These prorated personhour requirements are presented in Table 41, along with the recurring labor hours for each of the four preform/processing combinations.

4.3.2 Labor Costs

Manufacturing hours to produce the individual "Y"-spars are also tabulated in Table 41. Personhour estimates for the autoclave-consolidated -13 "Y"-spar are based on a single autoclave cycle being required, including an overnight preheating at 350°F. Personhours for the RTM and RFI/autoclave processes that were performed at a subcontractor were derived by dividing the vendor's cost to Grumman by a labor rate of $100.00 per hour. Similarly, personhours listed for the weaving and stitching of the -11 and -13 preforms were derived from the subcontractors' dollar costs to Grumman. The personhour estimates given in Table 41 are average values and do not reflect a learning curve.

Based on the tabulated data, personhour requirements for the four fabrication approaches are:

- RTM processing of D19B8220-15 "Y"-spar: 107.12 personhours
- Autoclave consolidation of D19B8220-13 "Y"-spar: 125.52 personhours
- RFI/autoclave processing of D19B8220-15 "Y"-spar: 102.00 personhours
- RFI/autoclave processing of D19B8220-11 replacement "Y"-spar: 130.91 personhours.

4.3.3 Material Costs

Most material costs for the "Y"-spars under the four competing preform/processing combinations were included in the data summarized in Table 41. Therefore, Table 42 includes only the material costs

TABLE 41 QUANTITATIVE COMPARISON OF PERSON HOURS REQUIRED TO FABRICATE Y-SPAR UNDER FOUR PREFORM/PROCESSING COMBINATIONS

MANUFACTURING ACTIVITY	PREFORM/PROCESSING COMBINATIONS				REMARKS
	KNITTED & STITCHED/ RTM	WOVEN & STITCHED/ AUTOCLAVED (TP)	KNITTED & STITCHED/ RFI/ AUTOCLAVED	WOVEN & STITCHED/ RFI/ AUTOCLAVED	
TOOL DESIGN & FABRICATION	1.89 hr	1.09 hr	2.00 hr	1.09 hr	HOURS ARE PRORATED FOR 100 UNITS
PREFORM FABRICATION					
• WEAVING 0°/90° CARCASS	N/A	68.85	N/A	68.85	BASED ON TOTAL COST: 6 FOR $41,310.00
• STITCHING ±45° PLIES	N/A	17.58	N/A	17.58	BASED ON COST OF $1,758.22 EACH
• KNITTING	70.43	N/A	N/A	N/A	
RTM FABRICATION: • TRIM TO FIT TOOL; LOAD IN TOOL; MIX, METER & INJECT RESIN; CURE; REMOVE PART	34.80	N/A	N/A	N/A	BASED ON COST OF $3,480.00
AUTOCLAVE CONSOLIDATION • TRIM TO FIT TOOL; LOAD IN TOOL; APPLY BREATHER & BAG; AUTOCLAVE CONSOLIDATE; REMOVE; TRIM PART	N/A	38.00	N/A	N/A	BASED ON ACTUAL HOURS EXPENDED
RFI/AUTOCLAVE PROCESSING • KNIT/STITCH PREFORM (IF APPLICABLE); APPLY FILM RESIN; PREPARE FOR AUTOCLAVE PROCESSING; AUTOCLAVE CURE; REMOVE; TRIM PART	N/A	N/A	100.00[1]	43.39[2]	1. BASED ON COST OF $10,000.00, WHICH INCLUDES THE COST OF THE KNITTED/ STITCHED PREFORM. 2 BASED ON COST OF $4,339.00
TOTALS	107.12 hr	125.52 hr	102.00 hr	130.91 hr	

NOTE: THE STANDARD AUTOCLAVE TAPE FABRICATION OF Y-SPAR REQUIRES 129 PERSON-HOURS

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associated with the autoclave consolidation of the -13 "Y"-spars at Grumman. These include costs of all breather and bagging materials required to support the autoclave operation itself, as well as the liquid nitrogen consumed in the autoclave cycle. The data are estimates based on observation of material usage during the bagging operation, or on average consumption of gas. From Table 42, the material costs for the autoclave manufacturing approach are $1767.00.

4.3.4 Facility Costs

The full-scale production of "Y"-spars, using each of the candidate manufacturing approaches, would require the following equipment:

TABLE 42 MATERIAL COST FOR AUTOCLAVE CONSOLIDATION OF – 13 Y-SPAR

MATERIAL (DESCRIPTION)	UNIT COST, $	USAGE	COST, $
BREATHER FABRIC (STYLE 181 FIBERGLASS)	1.50/YD²	10 YD²	15.00
VACUUM BAG SEALANT			
(HIGH-TEMPERATURE)	25/ROLL	6 ROLLS	150.00
(LOW-TEMPERATURE)	5/ROLL	2 ROLLS	10.00
VACUUM BAG FILM (KAPTON)	6/YD	4 YDS	24.00
KAPTON TAPE	28/ROLL	1 ROLL	28.00
INDUSTRIAL GAS & RELATED COST (LIQUID NITROGEN)	28/GAL	55 GAL	1540.00
TOTAL COST			1767.00

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- High-temperature/high-pressure autoclave
- Hydraulic press
- Vacuum pumps
- Metering/injection equipment to support RTM
- Other miscellaneous facilities to support the above capital equipment.

Isolating the costs of these types of facilities is beyond the scope of this program; therefore, they will not be further characterized.

4.3.5 Comparative Manufacturing Costs

Labor costs for the four manufacturing approaches, assuming a labor rate of $100.00 per hour, would be as follows:

- RTM-processed D19B8220-15 "Y"-spar: $10,712.00
- Autoclave-consolidated D19B8220-13 "Y"-spar: $12,552.00
- RFI/autoclave-processed D19B8220-15 "Y"-spar: $10,200.00
- RFI/autoclave-processed D19B8220-11 replacement "Y"-spar: $13,091.00.

Adding the separate material costs of $1767.00 to the autoclave consolidation approach, as identified above and in Table 42, would provide the following total comparative costs for the four preform/process combinations:

- RTM-processed D19B8220-15 "Y"-spar: $10,712.00
- Autoclave-consolidated D19B8220-13 "Y"-spar: $14,319.00
- RFI/autoclave-processed D19B8220-15 "Y"-spar: $10,200.00
- RFI/autoclave-processed D19B8220-11 replacement "Y"-spar: $13,091.00.

Based on the comparative manufacturing costs for each "Y"-spar and assuming applicability to future aerospace components, the RFI/autoclave process, with a knitted/stitched preform, could provide 5%, 29%, and 22% lower fabrication costs, respectively, than the other competing processes.

5 – SUBTASK 4: TESTS OF Y-SPARS

5.1 TEST SETUP

The Y-spar element was configured as a 35-in.-long by 10.8-in.-high beam. The beams have IM6/3501-6 graphite/epoxy caps mechanically fastened to the top of the Y-web. Load introduction was via aluminum attachment fittings sandwiched around the spar web and bolted in place. The specimen was loaded as a four-point bending beam by the fixture shown in Fig. 52. Two concentrated loads were applied 3.0 in. away from both sides of the midpoint of the 30.0-in. test span to provide a moment arm of 12 in. Strain measurements were obtained via ten axial and four three-element rosettes located back-to-back along the centerline of the beam (Fig. 53), except for the consolidated Y-spar. The AS4/PEEK commingled Y-spar had eight three-element rosettes and eight axial gages (Fig. 54). Concurrent with load application, midspan deflection was recorded with a dial gage. The spars were loaded to 50% limit load, unloaded, loaded to limit load, unloaded, loaded to ultimate load, held, and then loaded to failure.

5.2 TEST RESULTS

In general, the measured strains agreed well with the predictions. This is significant when one considers that the stiffness properties were derived from unidirectional tape properties with corrections made for fiber volume and the woven nature of the preform. Spar bending strains at failure were close to or exceeded ±6000 μin./in. in all cases. Whereas only the G40-800/Tactix 123 test specimen failed due to the load in the spar itself, this failure compared well with the average predicted value for an IM6/3501-6 unidirectional tape prepreg laminate, autoclave-cured.

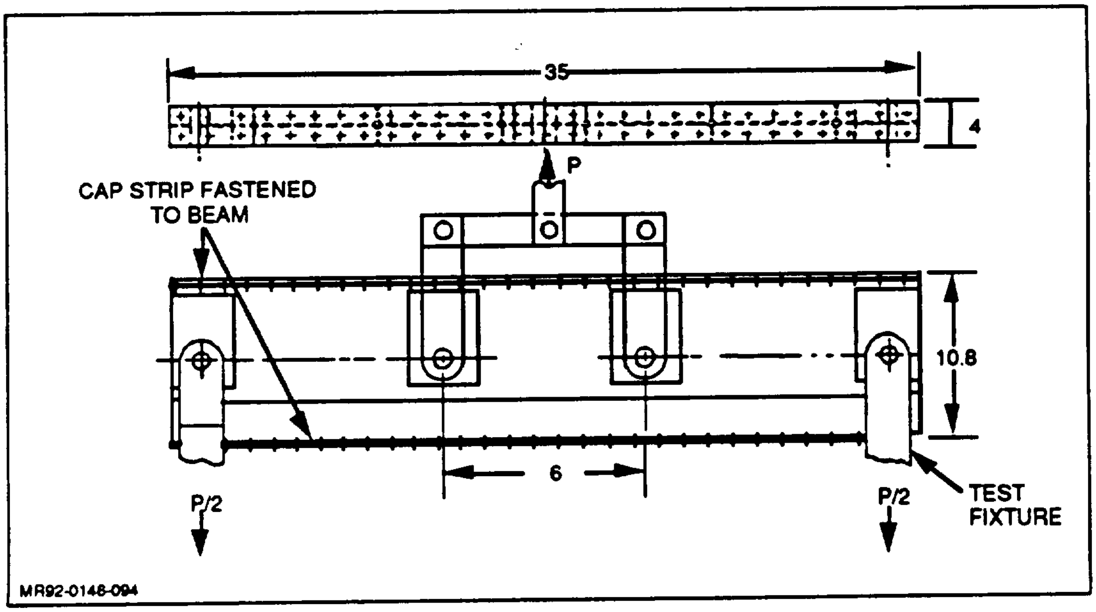

Fig. 52 Y-Spar 4-Point Bending Test Setup

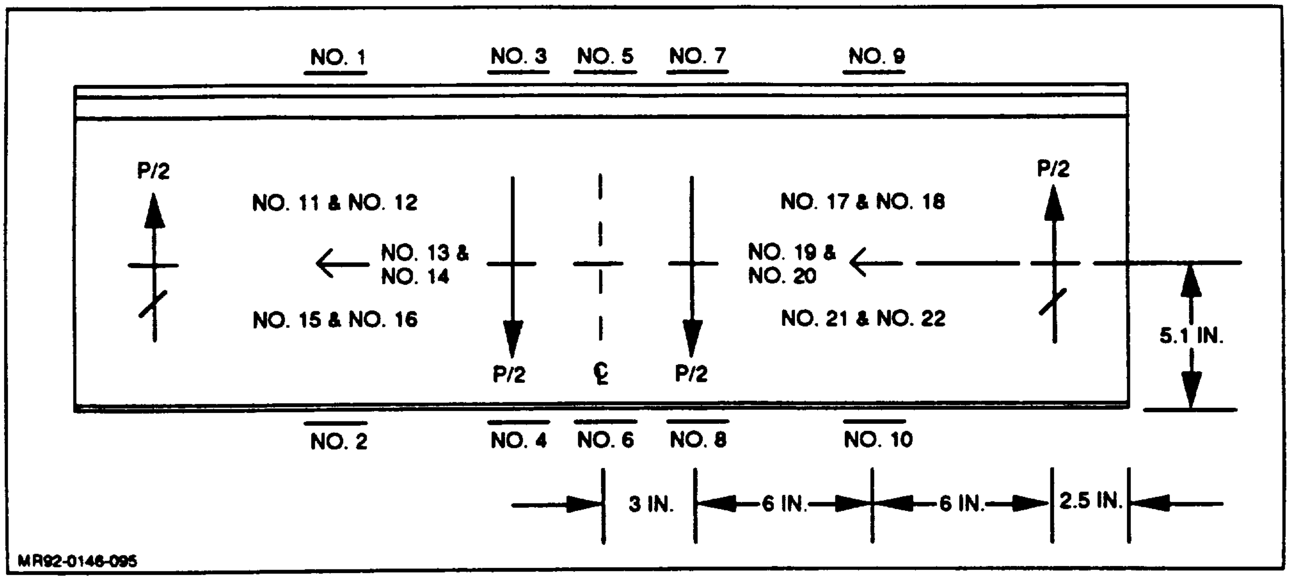

Fig. 53 Strain Gage Locations (Except for Woven AS4/PEEK Commingled Y-Spar)

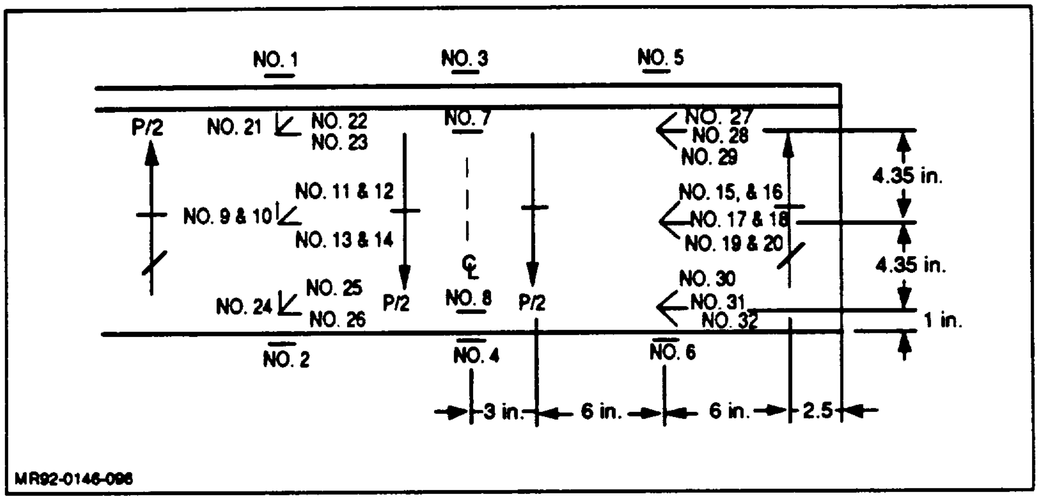

Fig. 54 Strain Gage Locations for Woven AS4/PEEK Commingled Y-Spar

5.2.1 Commingled AS4/PEEK 150g Y-Spar

The second oversize consolidated AS4/PEEK 150g Y-spar (D19B8220-13-2) was tested as a beam in four-point bending. The beam bending specimen was fabricated in accordance with Drawing No. D19B8221, except that the IM6/3501-6 Gr/Ep cap laminates were bonded to the spar flanges with HYSOL'S EA9394 adhesive. This was done because the flanges of the preform were narrower than specified and there was concern that the fastener edge distance would be too small and result in a premature shear-out failure of the fastener. Fasteners were put in over the load introduction and reaction plates to prevent peeling where the shear is discontinuous, between these locations to preclude a wrinkling disbond, and in the center portion to reflect the presence of holes in the critical region. The beam was instrumented with 32 strain gages as shown in Fig. 54. Mid-span deflection was measured with a dial gage.

After installation into the test machine, the beam was loaded to 24,000 lb (50% limit load) in 4000-lb increments and then unloaded along the same path. Measured strains were compared with predictions and checked for any anomalies. The comparison was good and the beam was then loaded to limit load and unloaded. Again, the measured strains were generally in good agreement with the predictions, repeatable, and linear with one exception – the tension strain gage (#4) on the beam cap at mid-span. The strain in this gage started increasing faster than the applied load. Since this was only one gage, the beam was loaded to ultimate load (72,000 lb), held, and then loaded to failure in 4000-lb increments. Failure occurred at a load of 89,000 lb or 124% of ultimate and was through the holes on the tension cap over the load introduction. The maximum tension strain (#4) was 8300 μin./in. and the maximum compression strain (#3) was -5950 μin./in., both at mid-span. Tables 43 through 45 list the most significant strains and Table 46 gives the mid-span deflection recorded during the three load runs. Predictions at limit load (above which most of the strains were nonlinear) for the gages in the outer panels of the beam are given for two laminates; the laminate called out on the drawing and a 11.8/41/47.2% (0°/±45°/90°) laminate obtained from the results of coupon testing. This laminate is discussed more fully later. Figures 55 through 58 are plots of strain versus test load and Fig. 59 plots deflection versus test load. Two possibilities exist for the nonlinearity of the strains; one is that the cap laminates, which have a high percentage of ±45° plies, became nonlinear above 4000 μin./in. due to the nonlinearity of the layer shear modulus, G_{12}, or that the response of the woven Y-spar itself was nonlinear due to its architecture. Figure 60 shows the test setup for the Y-spar four-point beam bending. Figure 61 shows the tension cap failure at 89,000 lb.

Following the test, the web of the Y-spar was cut up into tension, compression, and rail shear coupons to provide additional data on the basic properties of the woven/stitched commingled preform and the consolidation process. Table 47 gives the results of previous testing performed on a consolidated section of the basic 0/90 preform and Table 48 summarizes the web coupon test results. The anomalies in the test results, such as the low failure strain in warp tension (4600 μin./in.) and the low modulus (2.48 msi) for the 0/90 preform need further investigation. Elastic moduli predictions based on AS4/3501-6 Gr/Ep tape properties corrected for fiber volume differences and weaving as opposed to unidirectional tape are also tabulated. The 11.8/41/47.2% (0°/±45°/90°) laminate was determined from the following information. As designed, the webs of the AS4/PEEK and IM7/Tactix 123 "Y"-spars should have had 50% ±45° fabric layers but there are indications that this was not the case. A section of the web of the IM7 spar preform, made up of the 0/90 carcass and stitched ±45° fabric, weighed 40.38 grams and, of this, the 0/90 carcass weighed 24.15 grams, implying only 40% by weight for the ±45° fabric layers. In addition, a section of the AS4/PEEK (unconsolidated) carcass weighed 63.91 grams and the 0/90 carcass weighed 34.28 grams, implying 46% by weight for the ±45° fabric layers. Finally, the flanges were originally designed to be 75% of the web thickness but TTI predicted the web thickness would be 0.215 in. and that the flange would be 0.151 in. or 70% of the web thickness. This make sense if the 0/90 carcass makes up 60% of the total fiber. The 41% for the ±45° fabric layers is a result of ignoring the warp weavers when calculating the load-carrying percentages of the fibers.

TABLE 43 UPPER AND LOWER CAP STRAINS (MICROINCHES/INCH): D19B8220-13-2

LOAD, lb	STRAIN GAGES					
	#1(4)	#3	#5	#2	#4	#6
4000(1)	–139/–151	–247/–415	–132/–144	178/192	279/567	178/185
8000(1)	–252/–265	–474/–658	–246/–257	321/339	564/886	337/344
(2)	–236/–257	–441/–589	–229/–244	305/342	523/947	322/357
12000(1)	–372/–379	–734/–892	–363/–369	472/484	899/1189	495/500
(3)	–363	–709	–354	470	875	496
16000(1)	–492/–493	–1010/–1118	–479/–480	626/629	1257/1475	654/654
(2)	–468/–498	–912/–1119	–454/–479	602/648	1130/1665	634/681
20000(1)	–610/–608	–1281/–1338	–593/–591	779/777	1616/1743	809/807
24000(1)	–727	–1552	–705	934	1982	964
(2)	–705/–738	1418/–1640	–681/–711	908/952	1795/2360	950/999
(3)	–716	–1463	–694	924	1863	967
32000(2)	–936/–968	–1937/–2126	–905/–931	1208/1242	2515/3008	1255/1299
36000(3)	–1066	–2220	–1030	1368	2880	1429
40000(2)	–1179/–1196	–2479/–2588	–1136/–1145	1515/1530	3321/3606	1569/1589
44000(2)	–1317	–2773	–1265	1686	3748	1894
48000(2)	–1432	–3023	–1375	1828	4115	1895
(3)	–1429	–3008	–1375	1821	3959	1747
PREDICTION	–1410	–	–1410	1854	–	1854
52000(3)	–1550	–3273	–1490	1973	4335	2049
56000(3)	–1679	–3555	–1614	2135	4748	2218
60000(3)	–1800	–3830	–1730	2293	5154	2385
64000(3)	–1920	–4098	–1843	2450	5574	2547
68000(3)	–2043	–4377	–1957	2608	6006	2715
72000(3)	–2162	–4645	–2069	2763	6401	2878
76000(3)	–2282	–4923	–2182	2926	6840	3055
80000(3)	–2422	–5245	–2314	3112	7328	3238
84000(3)	–2539	–5542	–2432	3286	7765	3417
88000(3)	–2665	–5862	–2552	3462	8171	3600

(1) FIRST LOADING 0 – 24000 lb (50% LIMIT LOAD)
(2) SECOND LOADING 0 – 48000 lb (100% LIMIT LOAD)
(3) FAILURE LOADING 0 – 89000 lb
(4) STRAIN RECORDED WHILE LOADING/STRAIN RECORDED UNLOADING

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TABLE 44 ±45° STRAINS NEAR NEUTRAL AXIS (MICROINCHES/INCH)

LOAD, lb	STRAIN GAGES					
	#11(5)	#12	#19	#20	#15	#16
4000(1)	–221/–229	–238/–220	–197/–212	–226/–215	238/268	253/262
8000(1)	–410/–412	–404/–391	–396/–399	–397/–388	469/488	458/462
(2)	–382/–413	–387/–412	–386/–411	–370/–397	456/515	429/464
12000(1)	–598/–593	–585/–569	–586/–584	–575/–566	695/707	668/667
(3)	–597	–577	–582	–579	691	665
16000(1)	–785/–774	–769/–750	–774/–767	–752/–743	921/925	878/872
(2)	–756/–789	–757/–783	–758/–793	–727/–763	897/974	843/891
20000(1)	–972/–962	–957/941	–960/–954	–931/–923	1148/1143	1089/1079
24000(1)	–1162	–1146	–1151	–1113	1372	1300
(2)	–1132/–1161	–1131/–1155	–1141/–1167	–1094/–1122	1334/1417	1258/1307
(3)	–1164	–1140	–1151	–1122	1360	1293
32000(2)	–1503/–1524	–1502/–1527	–1500/–1540	–1436/–1476	1772/1856	1663/1721
36000(3)	–1716	–1704	–1705	–1652	2013	1906
40000(2)	–1883/–1873	–1892/–1889	–1880/–1894	–1802/–1820	2232/2271	2090/2115
44000(2)	–2090	–2111	–2096	–2015	2498	2337
48000(2)	–2264	–2291	–2282	–2198	2720	2542
(3)	–2278	–2290	–2273	–2206	2690	2545
PREDICTION (4)	–2019 (–2340)	–2019 (–2340)	–2019 (–2340)	–2019 (–2340)	2271 (2600)	2271 (2600)
52000(3)	–2466	–2487	–2462	–2397	2927	2763
56000(3)	–2666	–2698	–2665	–2601	3180	2996
60000(3)	–2866	–2908	–2865	–2803	3439	3232
64000(3)	–3058	–3111	–3054	–2997	3683	3454
68000(3)	–3258	–3322	–3255	–3203	3947	3690
72000(3)	–3451	–3531	–3454	–3410	4205	3923
76000(3)	–3662	–3752	–3658	–3624	4478	4167
80000(3)	–3879	–3983	–3873	–3850	4765	4423
84000(3)	–4094	–4216	–4088	–4080	5054	4678
88000(3)	–4296	–4440	–4277	–4312	5339	4921

(1) FIRST LOADING 0 – 24000 lb (50% LIMIT LOAD)
(2) SECOND LOADING 0 – 48000 lb (100% LIMIT LOAD)
(3) FAILURE LOADING 0 – 89000 lb
(4) PREDICTIONS BASED ON 11.8/41/47.2% LAMINATE
(5) STRAIN RECORDED WHILE LOADING/STRAIN RECORDED UNLOADING

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TABLE 45 STRAINS IN WEB NEAR CAPS (MICROINCHES/INCH)

LOAD, lb	STRAIN GAGES					
	#22(5)	#29	#27	#25	#32	#30
4000(1)	–254/–281	–263/–282	189/219	–80/–90	–77/–82	222/237
8000(1)	–457/–488	–492/–507	352/380	–143/–154	–150/–153	424/436
(2)	–428/–482	–469/–523	333/407	–130/–17	–140/–152	406/475
12000(1)	–671/–692	–721/–731	520/541	–212/–220	–224/–225	627/632
(3)	–665	–719	520	–205	–222	629
16000(1)	–888/–896	–950/–950	687/697	–282/–286	–300/–298	831/830
(2)	–846/–921	–916/–999	651/749	–266/–154	–286/–302	804/890
20000(1)	–1102/–1101	–1176/–1174	851/854	–353/–353	–373/–371	1031/1029
24000(1)	–1322	–1407	1017	–424	–448	1234
(2)	–1281/–1344	1380/–1457	982/1075	–412/–293	–441/–454	1216/1296
(3)	–1311	–1409	1011	–417	–450	1239
32000(2)	–1694/–1762	–1826/–1909	1303/1396	–549/–433	–592/–606	1612/1695
36000(3)	–1941	–2086	1492	–624	–672	1831
40000(2)	–2131/–2163	–2304/–2344	1655/1703	–555/–566	–746/–751	2036/2078
44000(2)	–2381	–2570	1850	–638	–831	2276
48000(2)	–2595	–2803	2023	–706	–906	2482
(3)	–2595	–2787	1992	–836	–901	2439
PREDICTION (4)	–2295 (–2610)	–2295 (–2610)	1666 (1950)	–969 (–1170)	–969 (–1170)	2102 (2360)
52000(3)	–2815	–3028	2167	–906	–984	2648
56000(3)	–3060	–3287	2359	–982	–1066	2876
60000(3)	–3296	–3544	2550	–1057	–1153	3107
64000(3)	–3525	–3791	2735	–1136	–1236	3328
68000(3)	–3754	–4050	2928	–1212	–1321	3552
72000(3)	–3989	–4308	3119	–1292	–1402	3778
76000(3)	–4235	–4577	3321	–1383	–1485	4014
80000(3)	–4486	–4874	3542	–1464	–1579	4270
84000(3)	–4747	–5148	3745	–1533	–1665	4513
88000(3)	–5001	–5440	3958	–1617	–1761	4760

(1) FIRST LOADING 0 – 24000 lb (50% LIMIT LOAD)

(2) SECOND LOADING 0 – 48000 lb (100% LIMIT LOAD)

(3) FAILURE LOADING 0 – 89000 lb

(4) PREDICTIONS BASED ON 11.8/41/47.2% LAMINATE

(5) STRAIN RECORDED WHILE LOADING/STRAIN RECORDED UNLOADING

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TABLE 46 MID-SPAN DEFLECTION (INCHES): AS4/PEEK Y-SPAR

LOAD (lb)	DEFLECTION, IN. FIRST LOADING 0 – 24,000 lb		SECOND LOADING 0 – 48,000 lb		FAILURE LOADING
4000	0.013	0.022			
8000	0.024	0.033	0.023	0.033	
12,000	0.036	0.043			0.040
16,000	0.048	0.052	0.042	0.055	
20,000	0.058	0.061			
24,000	0.080		0.063	0.085	0.070
32,000			0.083	0.096	
36,000					0.100
40,000			0.106	0.111	
44,000			0.119		
48,000			0.130		0.132
PREDICTION (1)			0.109 0.116		0.109 0.116
52,000					0.144
56,000					0.158
60,000					0.171
64,000					0.183
68,000					0.196
72,000					0.210
76,000					0.224
80,000					0.240
84,000					0.255
88,000					0.272

(1) PREDICTION BASED ON 11.8/41/47.2% LAMINATE

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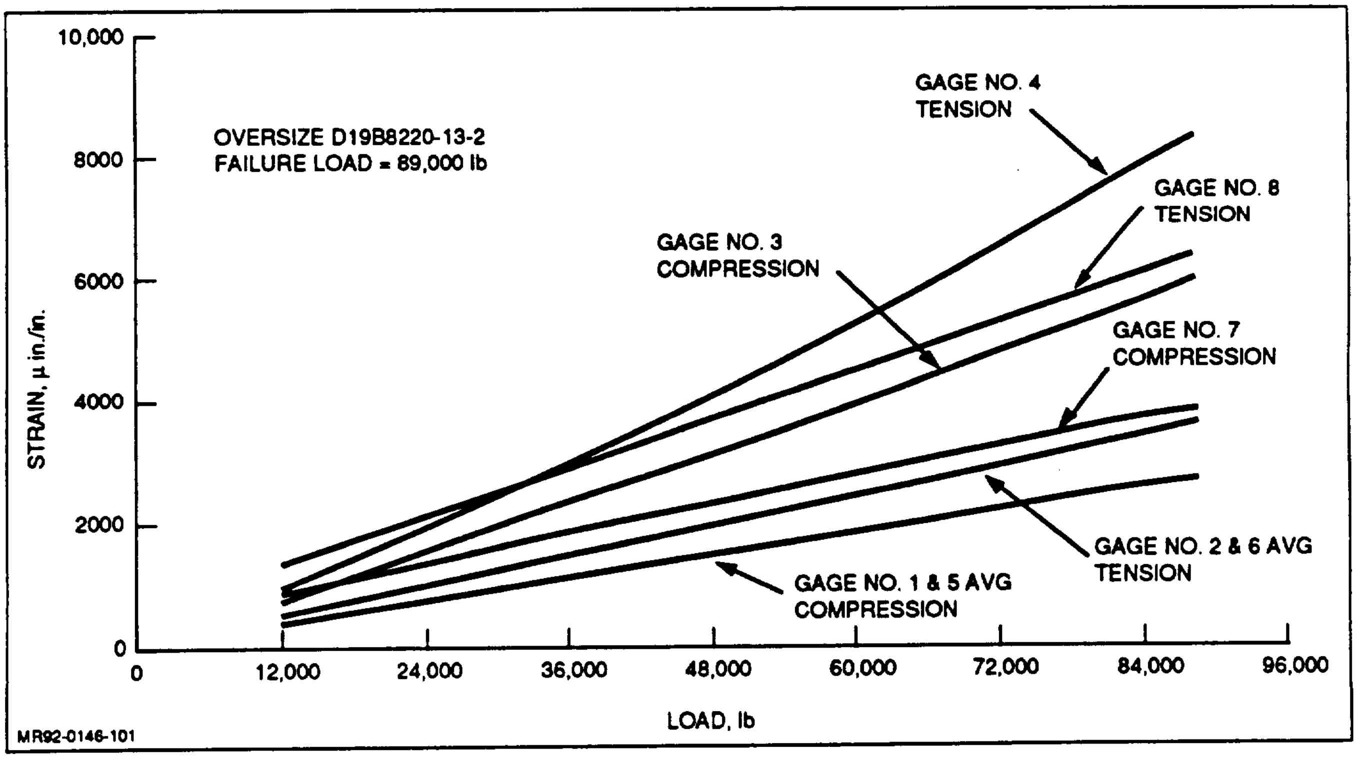

Fig. 55 Axial Strains in Caps and Center Portion of Web

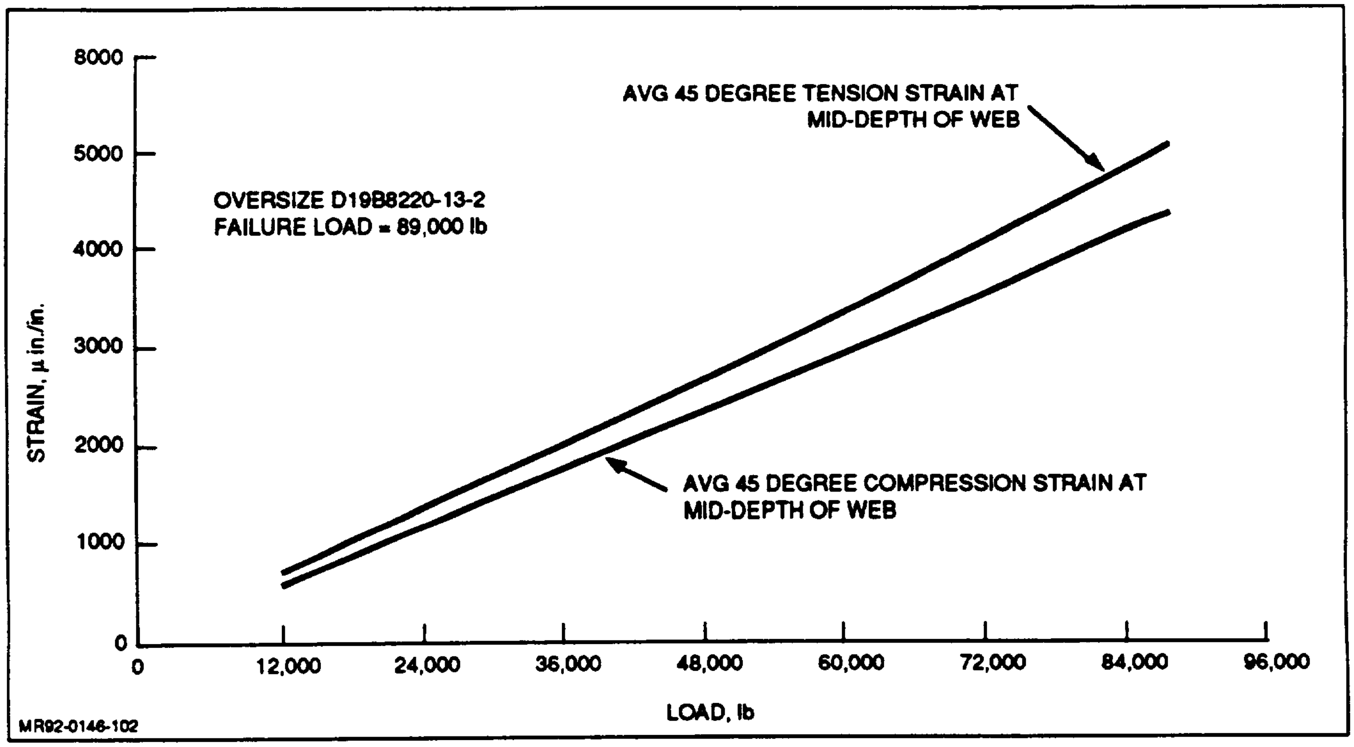

Fig. 56 45-Degree Strains in Web at Mid-Depth

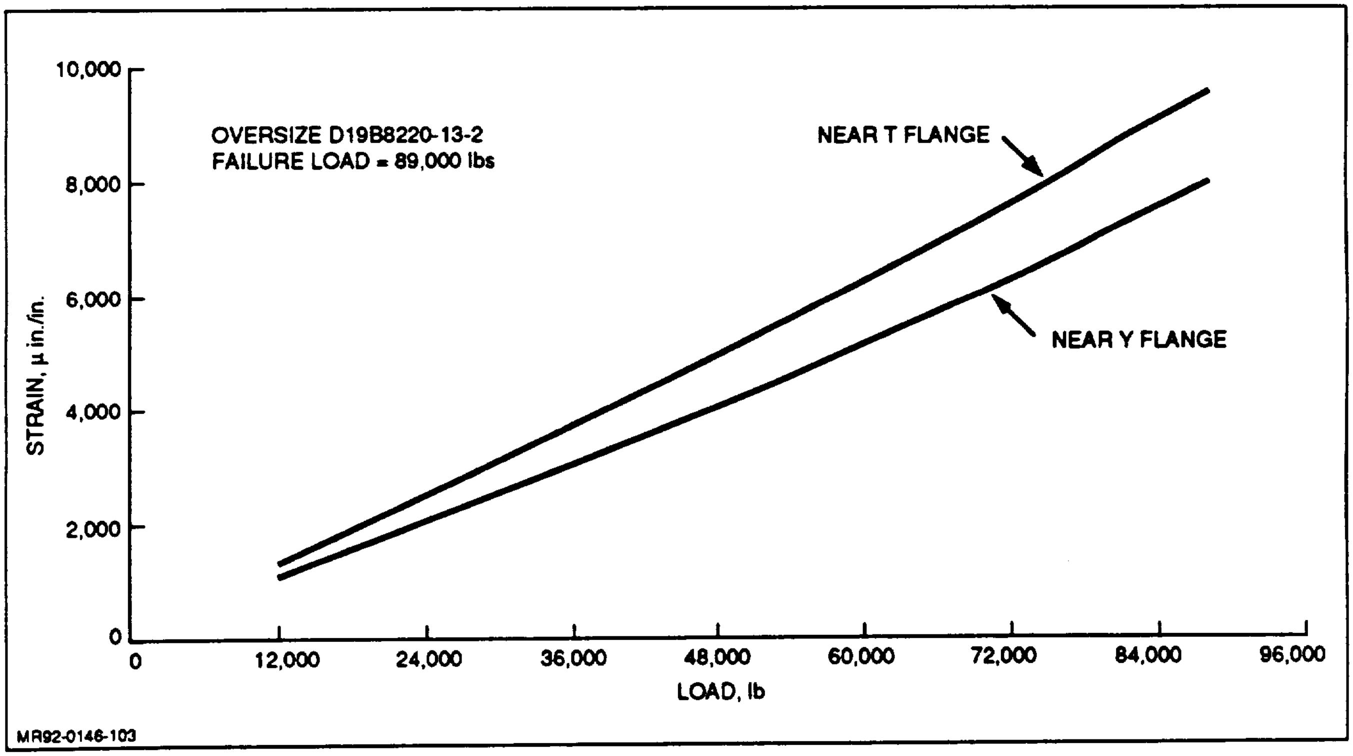

Fig. 57 Tension Strain in 45-Degree Fibers in Web

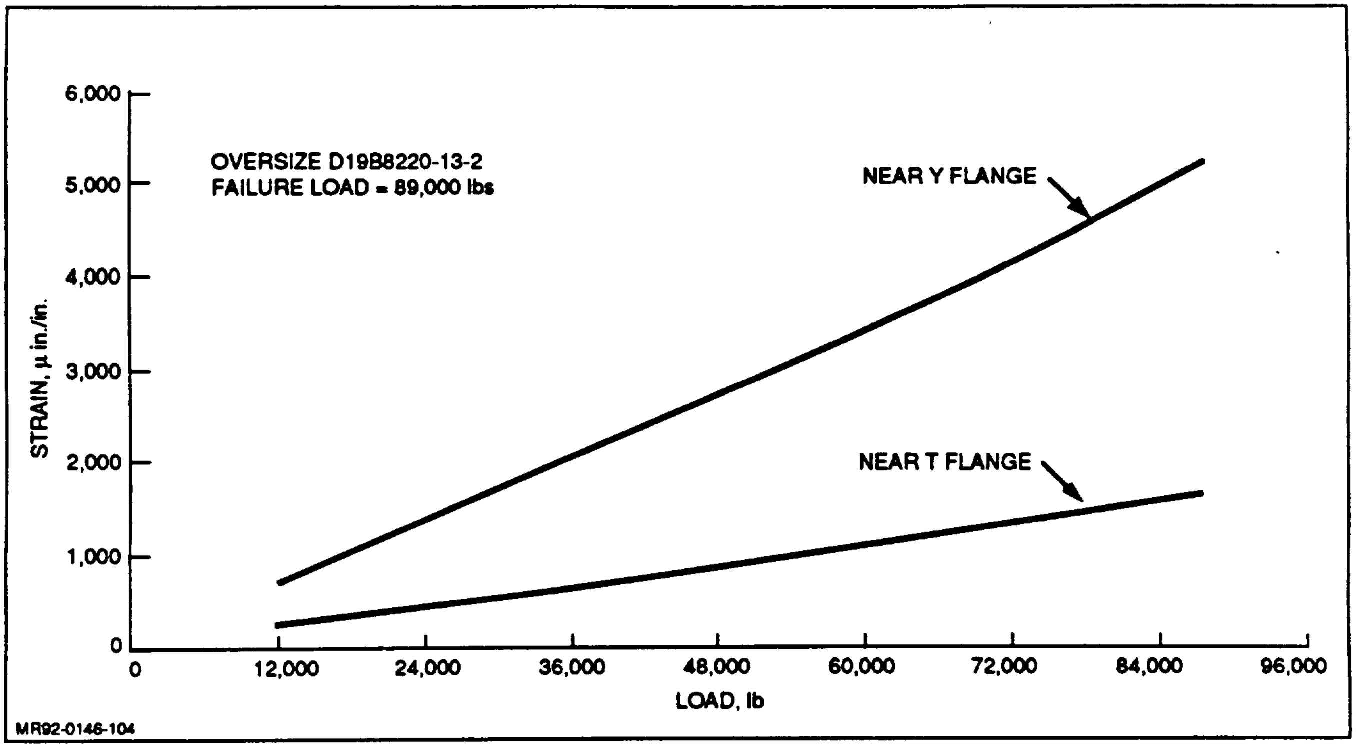

Fig. 58 Compression Strains in 45-Degree Fibers in Web

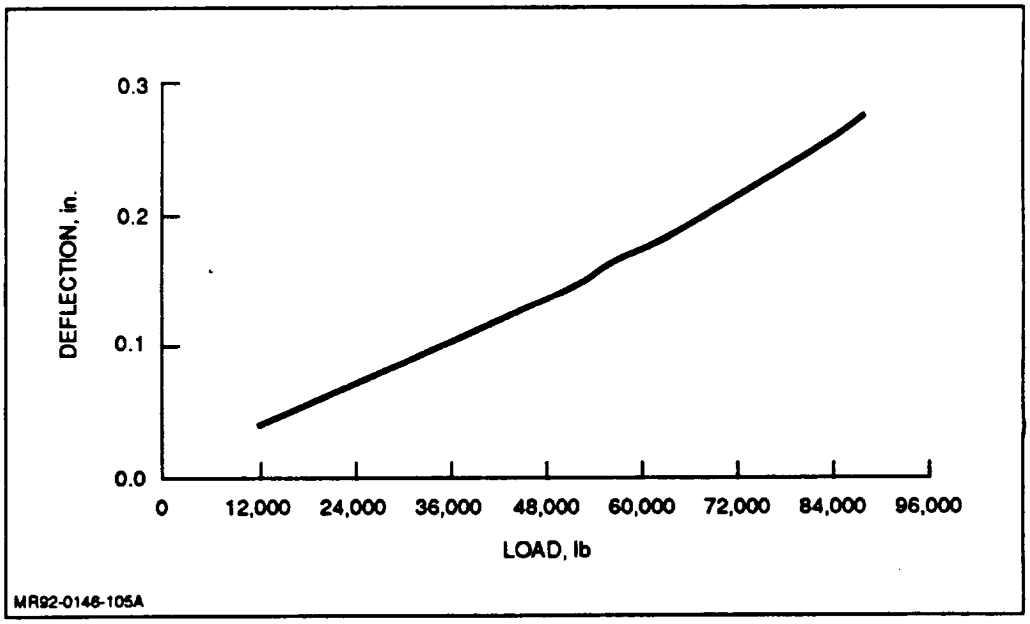

Fig. 59 Mid-Span Deflection Commingled AS4/PEEK Y-Spar

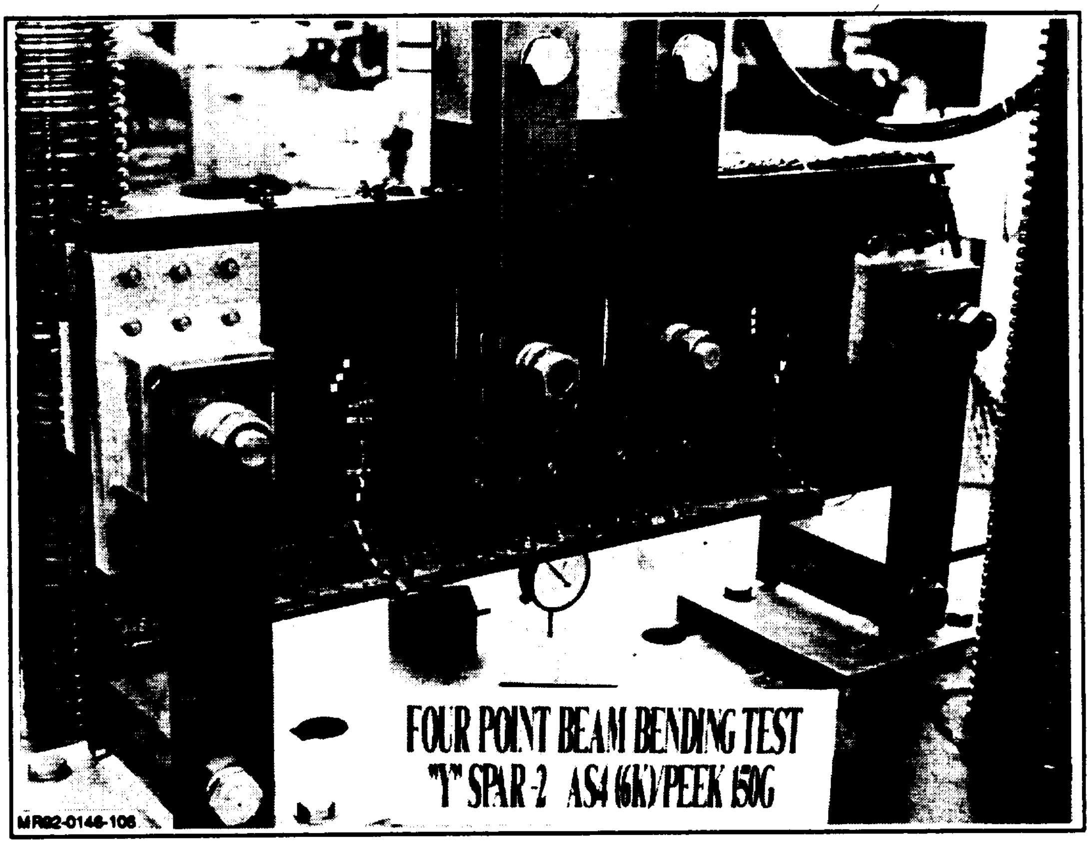

Fig. 60 Test Set-Up "Y"-Spar 4-Point Beam Bending

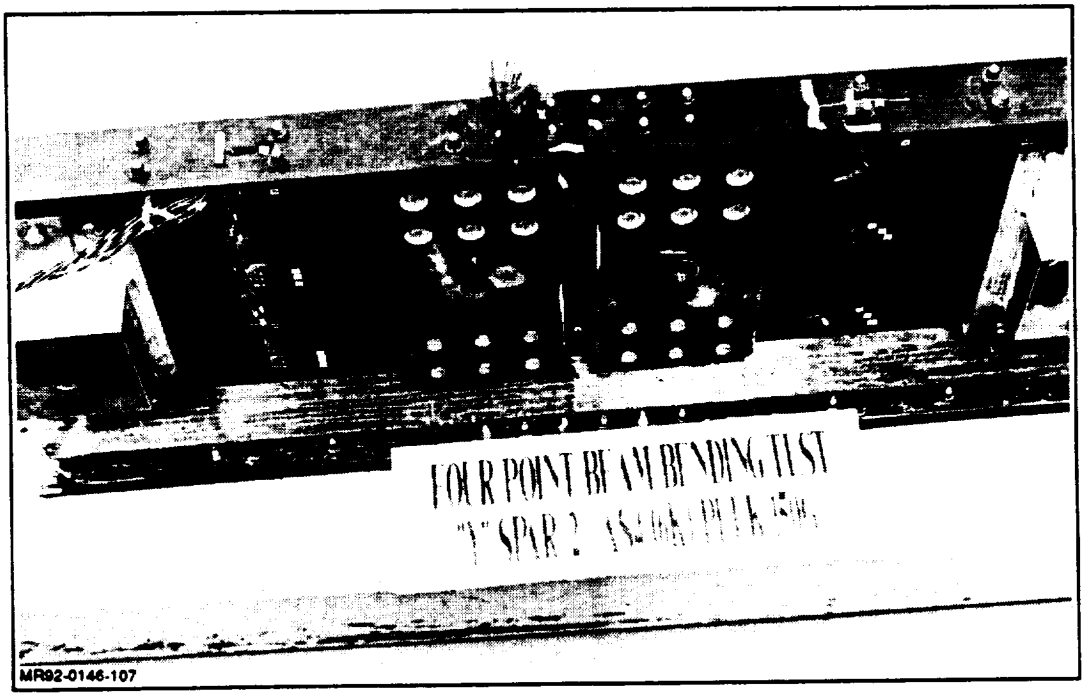

Fig. 61 Tension Cap Failure, P_{max} = 89,000 lb

TABLE 47 CONSOLIDATED 0/90 PREFORM COUPON RESULTS: AS4/PEEK 150G

TEST CONDITION	MODULUS, msi (1)	AVERAGE MODULUS, msi	PREDICTED MODULUS, (2)	FAILURE STRAIN, 10^{-6} in./in.	AVERAGE STRAIN, 10^{-6} in./in.
WARP TENSION	3.86 3.76 3.82	3.81	4.18	3920 4920 4970	4600
WARP COMPRESSION	2.82 2.35 2.27	2.48	3.99	10,700 16,100 14,300	13700
FILL COMPRESSION	14.09 11.90	13.00	12.04	8140 9310	8730

(1) MODULI NORMALIZED TO A THICKNESS OF 0.142 in. (AVERAGE OF 8 COUPONS)
(2) PREDICTIONS BASED ON 20/0/80% LAMINATE, 10% KNOCKDOWN FROM TAPE PROPERTIES TAKEN FOR WEAVING AND AN EFFECTIVE FIBER VOLUME = 53.42%

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TABLE 48 CONSOLIDATED WEB COUPON TEST RESULTS: AS4/PEEK 150G

TEST CONDITION	MODULUS, msi (1)	AVERAGE MODULUS, msi	PREDICTED MODULUS, msi(2)	FAILURE STRAIN, 10^{-6} in./in.	AVERAGE STRAIN, 10^{-6} in./in.	PREDICTED STRAIN(3), 10^{-6} in./in.
WARP TENSION	3.22 3.25 3.26	3.24	4.47	9770 9600 9610	9660	9000
FILL TENSION	11.96 10.46 12.02	11.48	9.56	6490 7630 6710	6940	8750
WARP COMPRESSION	3.99 4.18 3.50	3.89	4.25	10,500 10,600 10,700	10600	8936
FILL COMPRESSION	8.63 8.94 8.29	8.62	9.00	6810 6510 8220	7180	8778
RAIL SHEAR	1.62 1.51	1.57	2.10			

(1) MODULI NORMALIZED TO A THICKNESS OF 0.241 in. (AVERAGE OF 18 COUPONS)
(2) PREDICTIONS BASED ON 11.8/41/47.2% LAMINATE, 10% KNOCKDOWN FROM TAPE PROPERTIES TAKEN FOR WEAVING AND AN EFFECTIVE FIBER VOLUME = 56.8%
(3) AS4/3501-6 Gr/Ep FABRIC DESIGN LAYER PROPERTIES

MR92-0146-111

5.2.2 Knitted/Stitched G40-800/3501-6 (RFI) Y-Spar

The third G40-800 knitted/stitched "Y"-spar (D19B8220-15 RFI S/N 3) impregnated with 3501-6 resin by resin film infusion was tested as a beam in four-point bending. The beam bending specimen was fabricated in accordance with Drawing No. D19B8221 and instrumented with 22 strain gages as shown in Fig. 53. The beam weight was 4.86 lb. and its fiber volume 57.3%. Mid-span deflection was measured with a dial gage. After installation into the test machine, Fig. 62, the beam was loaded to 7000 lb (50% limit load) in 2000-lb increments and then unloaded. Measured strains were compared with predictions and checked for any anomalies. The comparison was good and the beam was then loaded to limit load and unloaded. Again, the measured strains were generally in good agreement with the predictions, repeatable, and linear. The beam designed to be buckling-critical was loaded to ultimate load (21,000 lb) which corresponds to shear buckling of the unsupported web, held, and then loaded to failure. Failure occurred at a load of 76,000 lb or 3.6 times the design buckling load and was due to the compressive stress in the cap as shown in Fig. 63. The maximum tension strain (#6) was 11,550 μin./in. and the maximum compression strain (#5) was -6128 μin./in. The maximum mid-span deflection was 0.347 in. Table 49 lists the difference in strains measured at an applied load of 42,000 lb (twice ultimate) and 21,000 lb (ultimate) and the predictions for Design Ultimate Load (21,000 lb). This was done to compensate for any errors in the strain-gage response at low strain as the load was initially applied. While gages #4, #6, and #8 should have been the same analytically, this was not the case due to the local stiffening effect of the load introduction plates. Figures 64 through 67 are plots of strain versus test load for the compression gages, the tension gages, and the two pairs of rosettes, respectively. Judging from these plots, the unfailed web did not buckle while the failed web buckled at a load of 70,000 lb. This result compares favorably with the G40-800 knitted/stitched "Y"-spar fabricated with Tactix 123 resin by resin transfer molding (D19B8220-15-1), which buckled at a load of 60,000 lb. At 70,000 lb, the average shear flow in the web was 3320 lb/in. The predicted shear only buckling load for the panel, which was 7 in. by 9.7 in., was determined for three cases; infinitely long clamped, finite length clamped, and finite length simply-supported. This was done to bound the problem of predicting buckling. For the infinitely long panel with all edges clamped (done to try to account for the fact that the web is clamped by the load and reaction plates but not by the tension flange or Y-flange), buckling was predicted to occur at a shear flow of 3530 lb/in. The finite length clamped panel had a predicted buckling load of 4780 lb/in., while the finite length simply-supported panel had a predicted buckling load of 3530 lb/in. Thus, buckling of the spar compares well with predictions.

Failure occurred at a load of 76,000 lb. The failure was the result of localized bending in the IM6/3501-6 compression cap laminate in front of the bolts located approximately 12 in. from the end of the spar. Due to the shear deformation of the outer panels relative to the central panel, there is a kink in the deflected shape of the cap. This kink is smoothed out by local bending. Further aggravating the kinking problem is the tendency of the load introduction plates to try to suppress the otherwise normally occurring curvature of the cap.

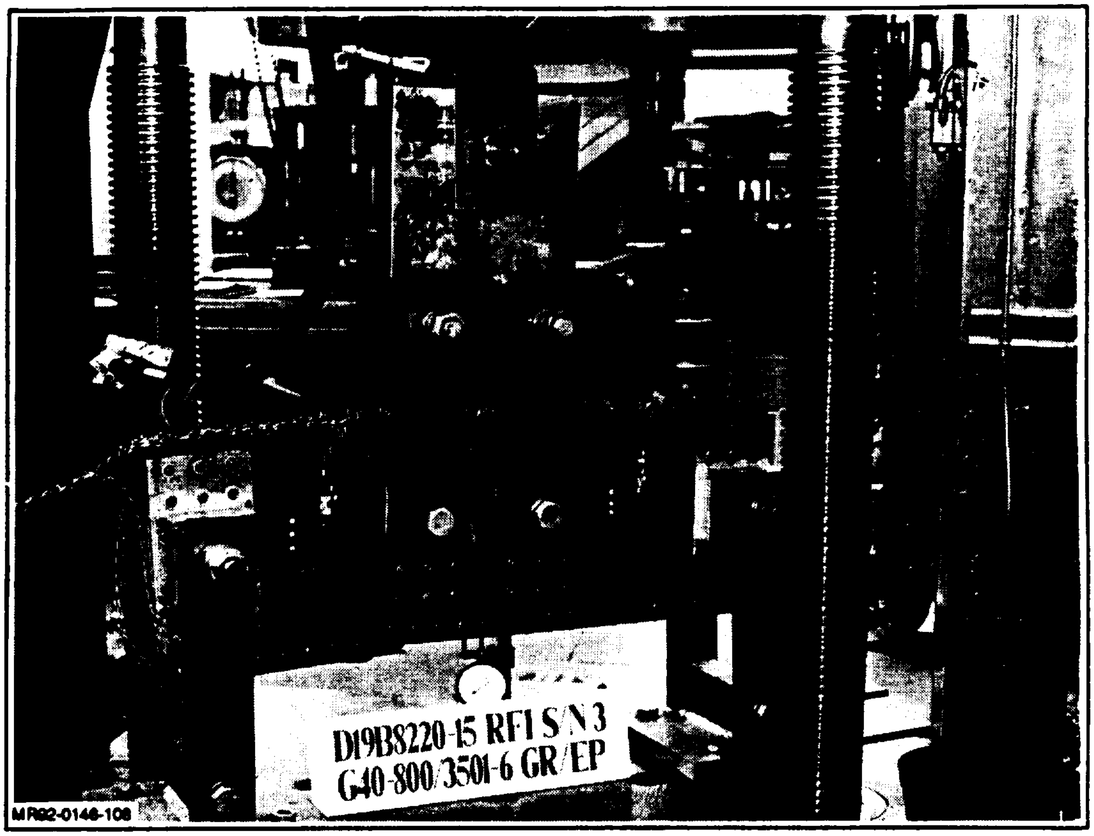

Fig. 62 Test Set-Up "Y"-Spar 4-Point Beam Bending

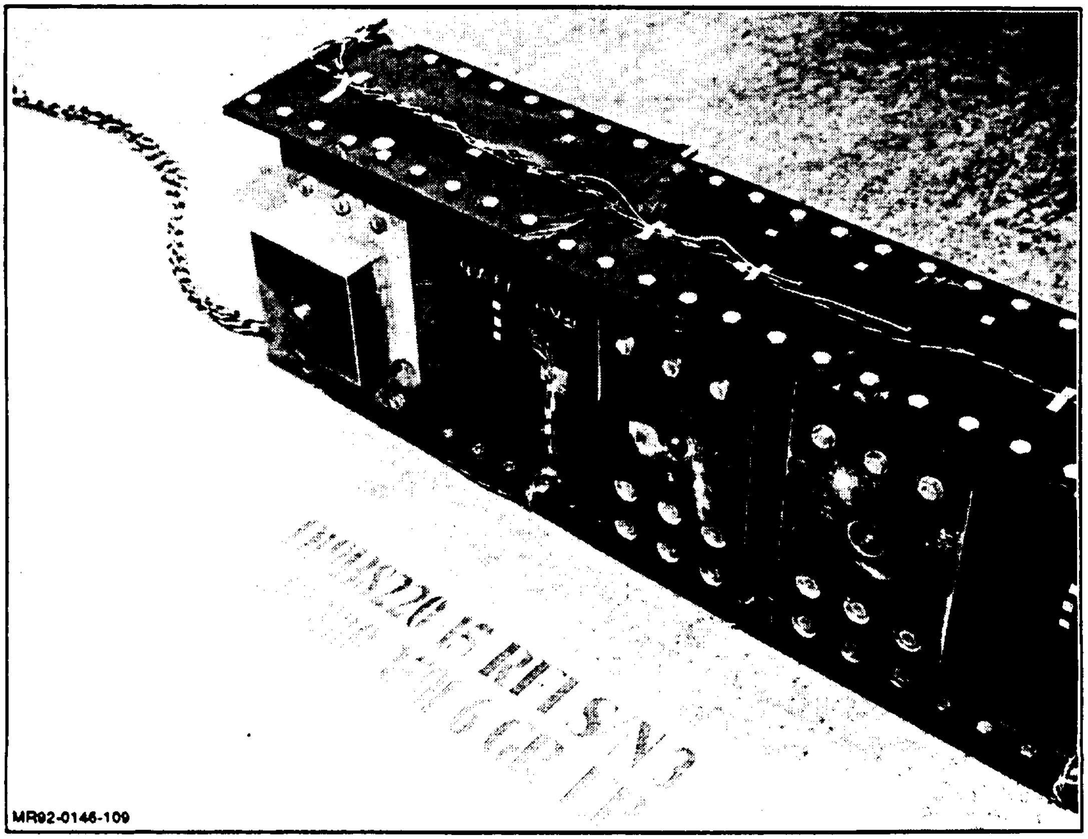

Fig. 63 "Y"-Spar Compression Cap Failure at 6,128 μ in./in.

TABLE 49 MEASURED AND PREDICTED STRAIN AT ULTIMATE LOAD: G40-800/3501-6 (RFI)

GAGE #	MEASURED STRAIN, (1) 10^{-6} in./in.	PREDICTED STRAIN, 10^{-6} in./in.
1	−790	−870
2	1095	1270
3	−1541	−1740
4	2076	2530
5	−1616	−1740
6	2911	2530
7	−1525	−1740
8	2042	2530
9	−792	−870
10	1209	1270
11	−1161	−915
12	−861	−915
13	30	255
14	216	255
15	1049	1090
16	1229	1090
17	1146	1090
18	1053	1090
19	277	255
20	107	255
21	−895	−915
22	−1048	−915

(1) MEASURED STRAINS ARE THE DIFFERENCE BETWEEN AN APPLIED LOAD OF 42,000 lb AND 21,000 lb

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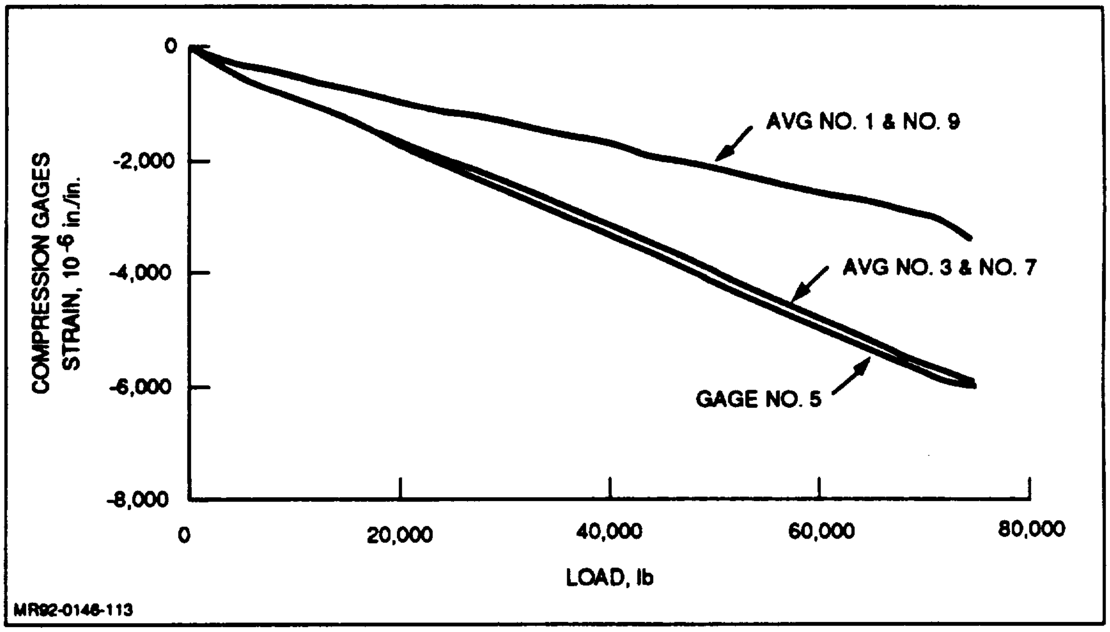

Fig. 64 Compression Strain vs Load: G40-800/3501-6 Knitted/Stitched (RFI) Y-Spar

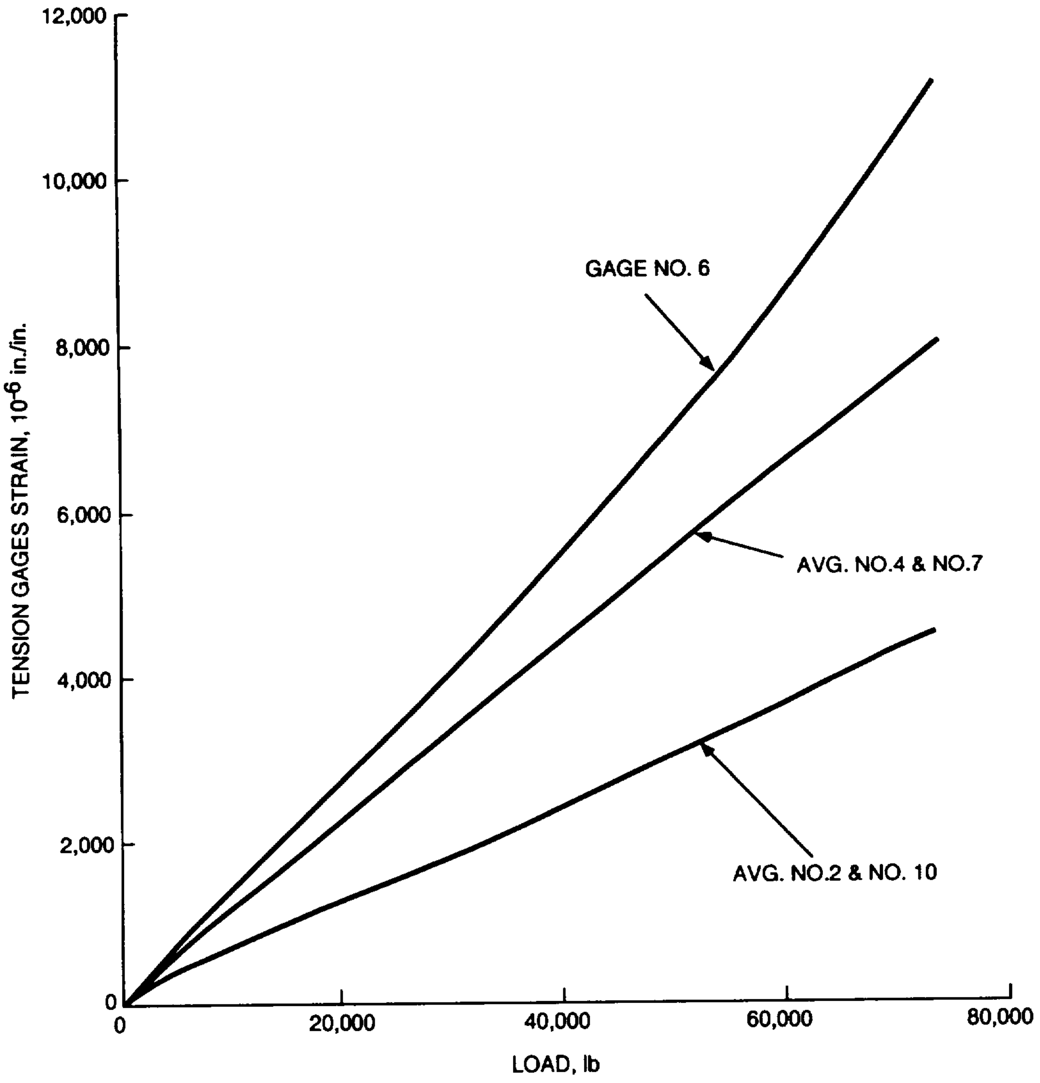

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Fig. 65 Tension Strain vs Load: G40-800/3501-6 Knitted/Stitched (RFI) Y-Spar

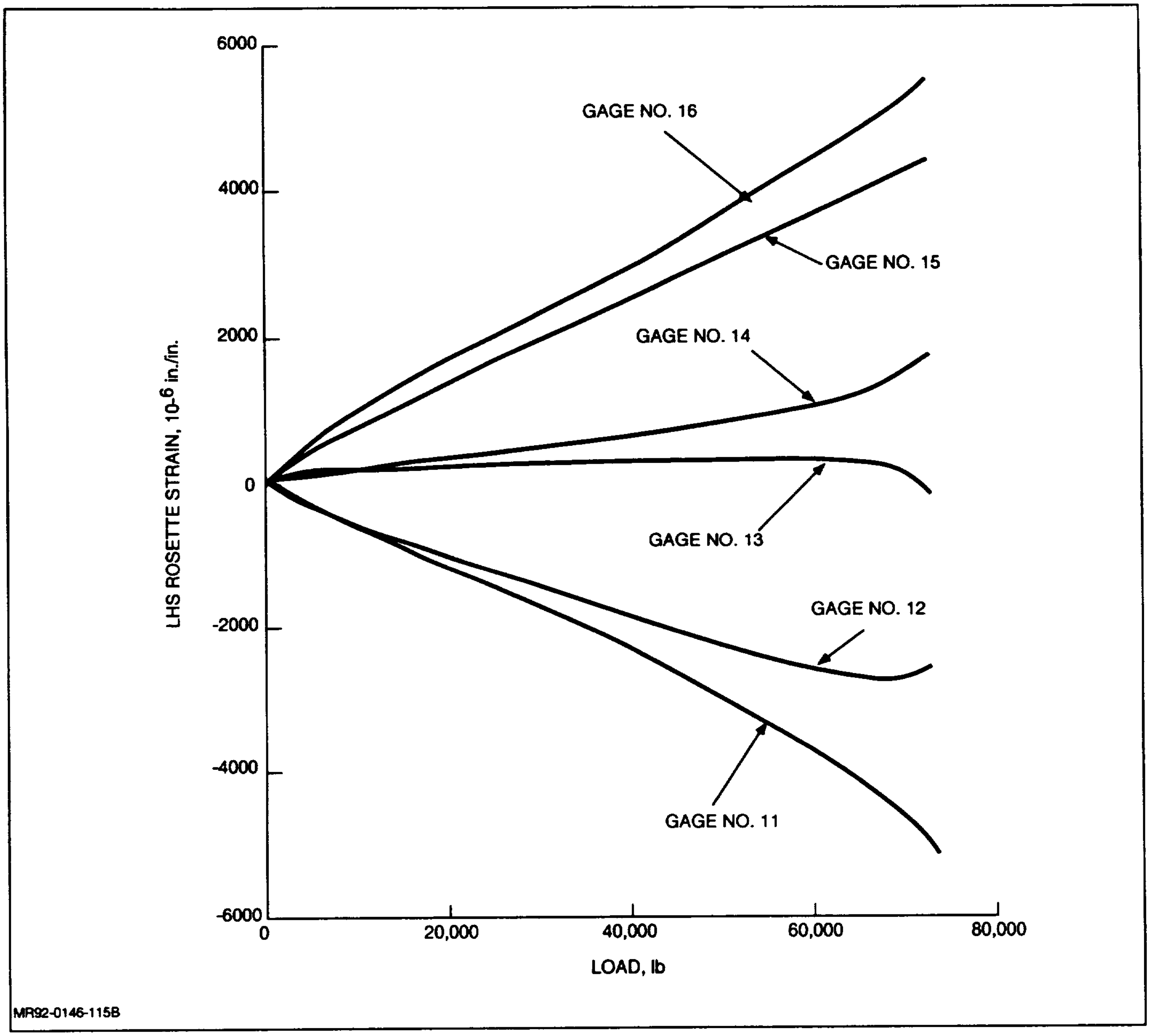

Fig. 66 LHS Rosette Strain vs Load: G40-800/3501-6 Knitted/Stitched (RFI) Y-Spar

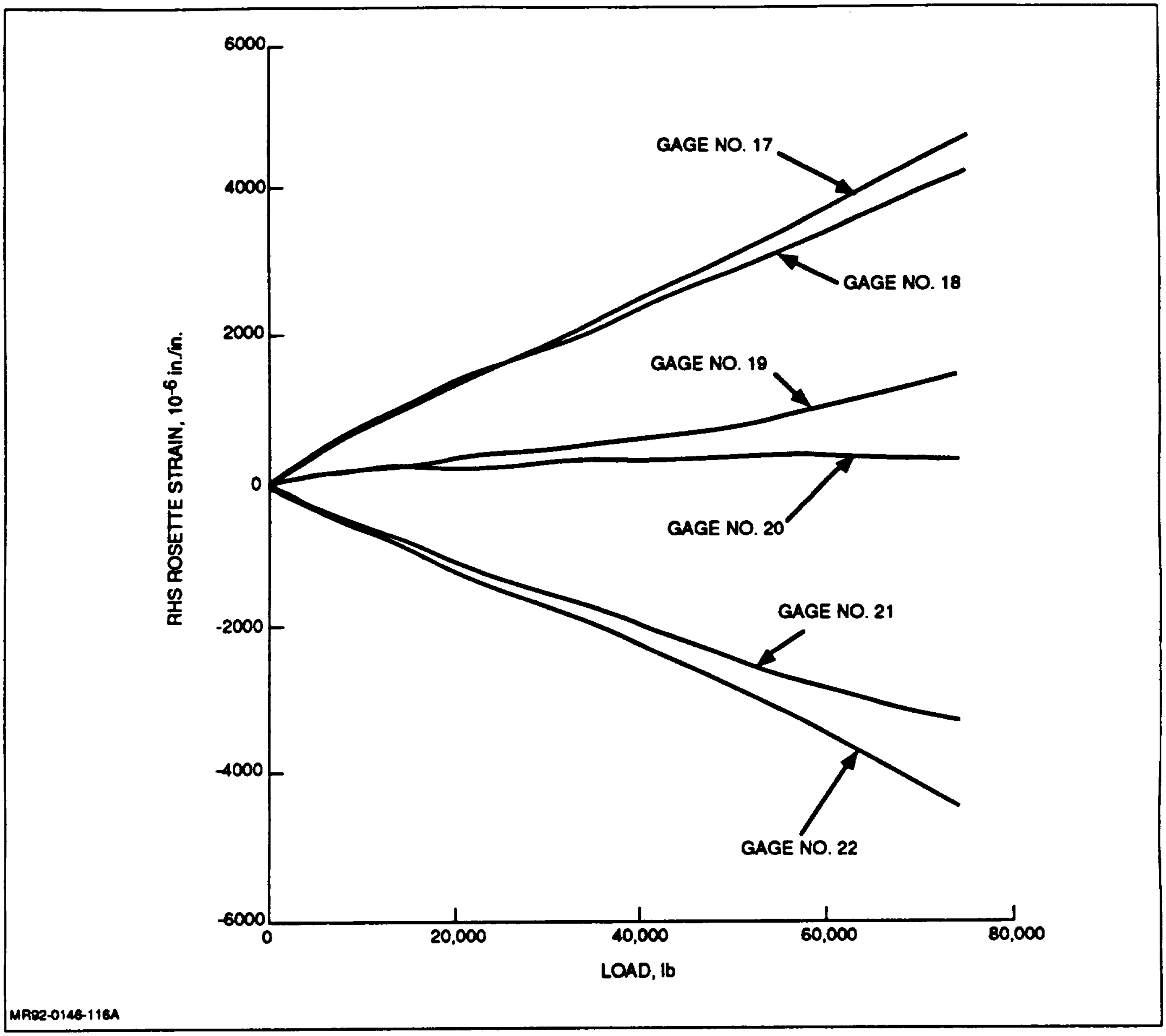

Fig. 67 RHS Rosette Strain vs Load: G40-800/3501-6 Knitted/Stitched (RFI) Y-Spar

5.2.3 Knitted/Stitched G40-800/Tactix 123 (RTM) Y-Spar

The next spar to be tested in four-point bending was the G40-800 knitted/stitched Y-spar (D19B8220-15-1) fabricated with Tactix 123 resin by resin transfer molding. The beam bending specimen was assembled in accordance with Drawing No. D19B8221 and instrumented with 22 strain gages as shown in Fig. 53. Mid-span deflection was measured with a dial gage. After installation into the test machine, Fig. 68, the beam was loaded to 7000 lb (50% limit load) in 1000 lb increments and then unloaded along the same path. Measured strains were compared with predictions and checked for any anomalies. The comparison was good and the beam was then loaded to limit load and unloaded. Again, the measured strains were generally in good agreement with the predictions, repeatable, and linear. The beam was loaded to design ultimate load (21,000 lb) which corresponds to shear buckling of the unsupported beam web at 1015 lb/in. held, and then loaded to failure. Failure occurred at a load of 65,300 lb or 311% of design ultimate and was due to shear strength failure of the web as shown in Fig. 69. The maximum tension strain (#6) was 9577 μin./in. and the maximum compression strain (#3) was -5716 μin./in. Maximum mid-span deflection was 0.285 in. Table 50 lists the strains recorded at ultimate load and the predictions. While gages #3, #5, and #7 as well as gages #4, #6, and #8 should have been the same conceptually, they differed due to the local stiffening effect of the load introduction plates. Figures 70 through 73 are plots of strain versus test load for the compression gages, the tension gages, and the two rosettes. It was determined from these plots that buckling of the outer web panels occurred at a test load of 60,000 lb. At this load, the average shear flow in the web was 2840 lb/in. The predicted shear buckling load for the panel, which was 7 in. by 9.7 in. was determined for three cases; infinitely long clamped, finite length clamped, and finite length simply-supported. This was done to bound the problem of predicting buckling. For the infinitely long panel with all edges clamped (done to try to account for the fact that the web is clamped by the load and reaction plates but not by the tension flange or Y-flange), buckling was predicted to occur at a shear flow of 2870 lb/in. The finite length clamped panel had a predicted buckling load of 3890 lb/in., while the finite length simply-supported panel had a predicted buckling load of 2870 lb/in. Thus, buckling of the spar compares very well with predictions.

The shear failure intersects the edge of the load introduction plate approximately 6.6 in. above the bottom of the tension flange. Analytically, the neutral axis is 6.42 in. above the bottom of the tension flange. This is verified fairly well by the good correlation between predicted and measured strains for the caps. The shear stress at this location is analytically 24,500 psi. Based on the shear strain measured by the rosettes on the webs, which indicates that the shear flow differed from a VQ/I distribution, this value should be corrected to 31,850 psi. Normalizing this stress to a fiber volume of 62% (the "Y"-spar fiber volume was 57%) gives a final shear stress of 34,640 psi. The average value of shear strength for autoclave-cured IM6/3501-6 is 33,750 psi, indicating that the failure was due to high shear stresses in the web.

5.2.4 Woven/Stitched IM7/3501-6 Gr/Ep (RFI) Y-Spar

The last beam tested in four-point bending was the IM7 woven Y-spar (D19B8220-11) impregnated with 3501-6 resin by resin film infusion. The beam bending specimen was fabricated in accordance with Drawing No. D19B8221 and instrumented with 22 strain gages as shown in Fig. 53. Mid-span deflection was measured with a dial gage. After installation into the test machine, Fig. 74, the beam was loaded to 7000 lb (50% limit load) in 2000-lb increments and then unloaded. Measured strains were compared with predictions and checked for any anomalies. The beam was then loaded to limit load and unloaded. The measured strains were generally lower than the predictions but repeatable and linear. The beam was loaded to ultimate load (21,000 lb), held, and then loaded to failure. Failure occurred at a load of 69,200 lb and was due to the tensile stress in the cap as shown in Fig. 75. The maximum tension strain (#6) was 8470 μin./in. and the maximum compression strain (#5) was -4770 μin./in. Maximum mid-span deflection was 0.258 in. Figures 76 through 79 are plots of predicted and measured strain versus test load for the compression gages, the tension gages, and the two pairs of rosettes. The predictions were made using a slightly modified laminate which accounted for the measured fiber volume (56.1%) and thickness of the web.

The failure was the result of combined bolt load and passing tension in the IM6/3501-6 tension cap laminate ~ 12 in. from the end of the spar. Based on strain gage #8, the strain at failure was 6600 μin./in. The predicted average tensile failure strain determined from HOLES (analyzes holes in composites) was 7070 μin./in. Therefore, actual and predicted failure agreed very well within the scatter of the test data.

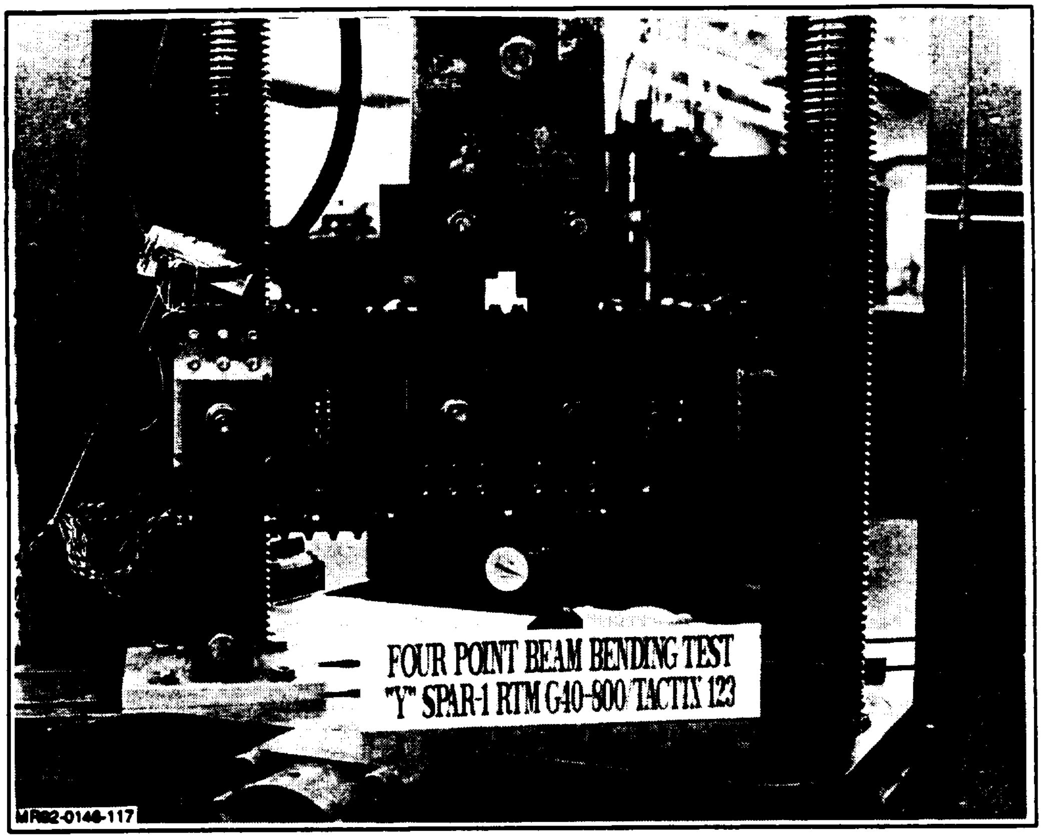

Fig. 68 Test Set-Up "Y"-Spar 4-Point Beam Bending (G40-800/Tactix 123 RTM)

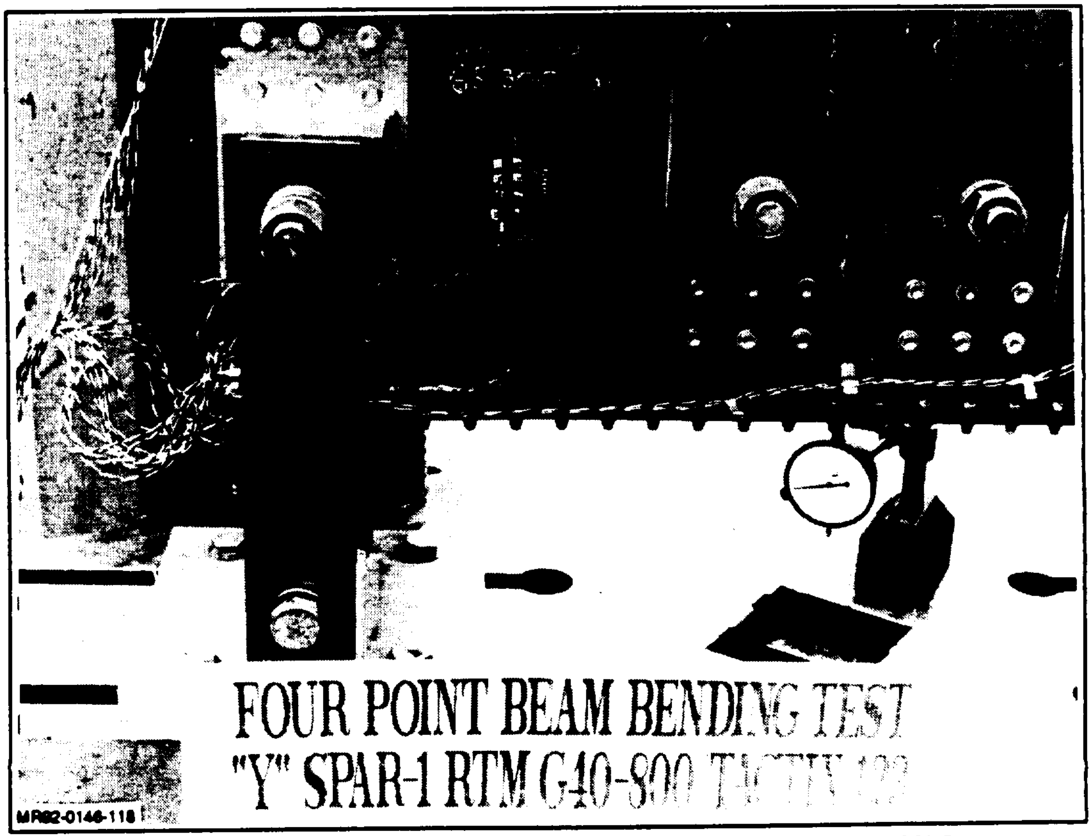

Fig. 69 Web Failure In Knitted & Stitched G40-800/Tactix 123 RTM Y-Spar

TABLE 50 MEASURED AND PREDICTED STRAIN AT ULTIMATE LOAD: G40-800/TACTIX 123 (RTM)

GAGE #	STRAIN, AT ULTIMATE LOAD, 10^{-6} in./in.	PREDICTED STRAIN, 10^{-6} in./in.
1	−906	−870
2	1206	1270
3	−1651	−1740
4	2276	2530
5	−1590	−1740
6	2542	2530
7	−1581	−1740
8	2336	2530
9	−832	−870
10	1218	1270
11	−1196	−915
12	−1240	−915
13	249	255
14	204	255
15	1351	1090
16	1414	1090
17	−1045	−915
18	−1291	−915
19	376	255
20	215	255
21	1304	1090
22	1295	1090
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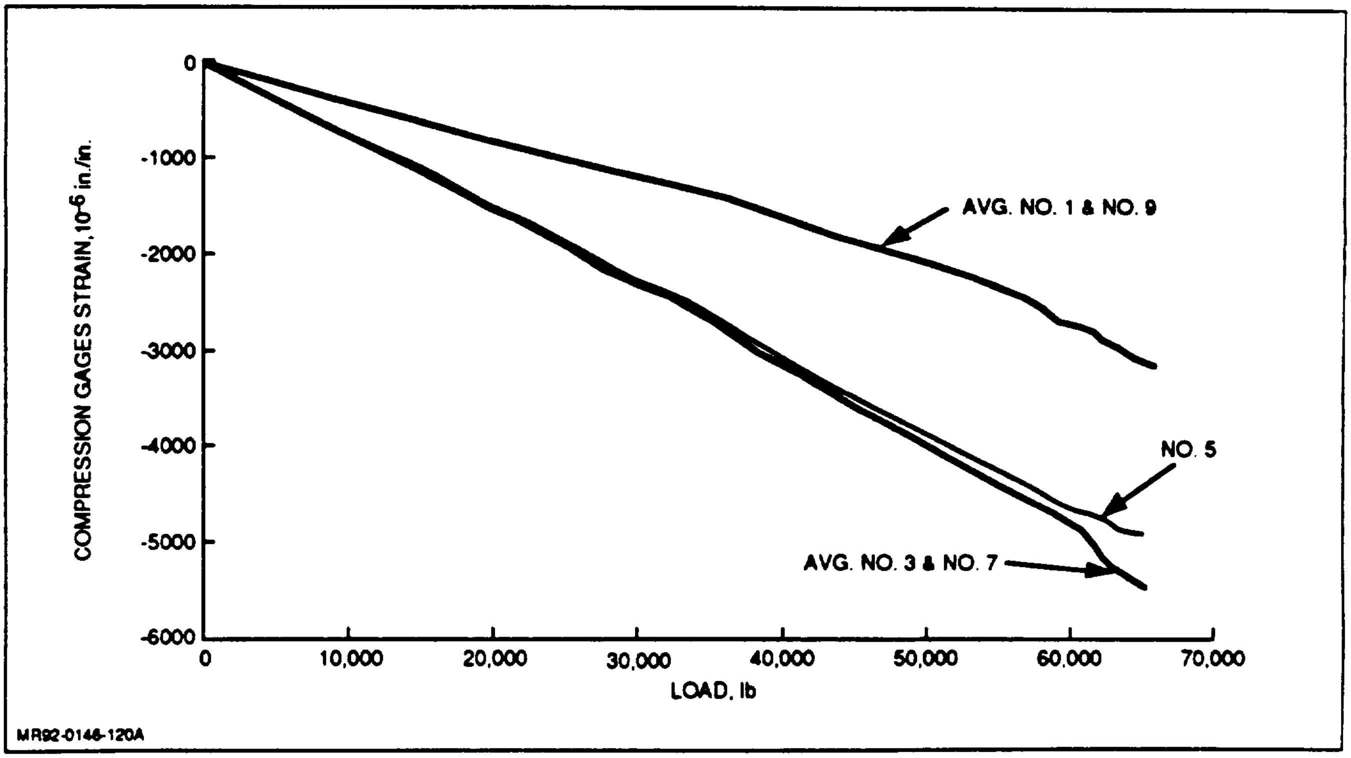

Fig. 70 Compression Strain in Cap of G40-800/Tactix 123 (RTM) Y-Spar

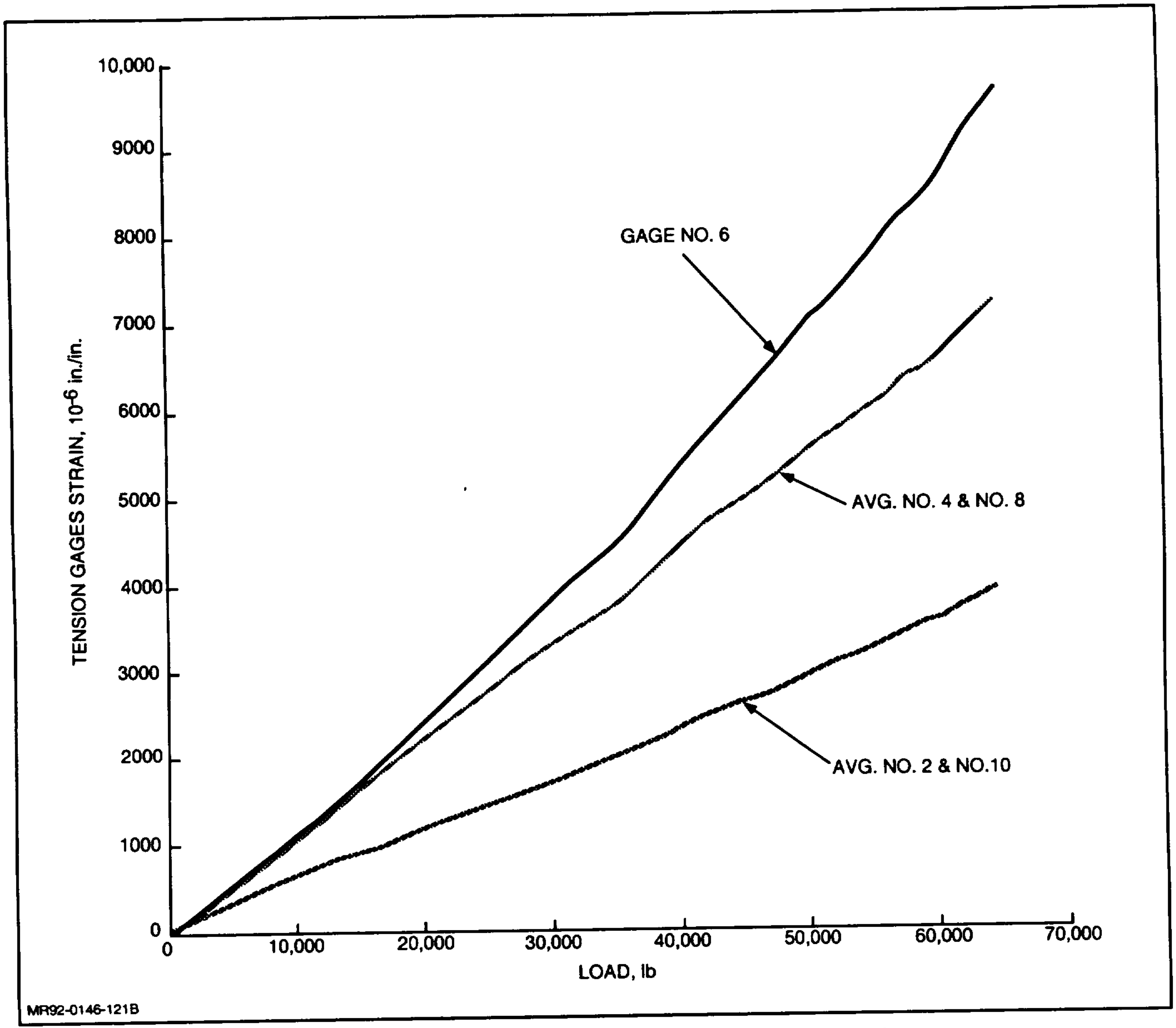

Fig. 71 Tension Strain in Caps: G40-800/Tactix 123 (RTM) Y-Spar

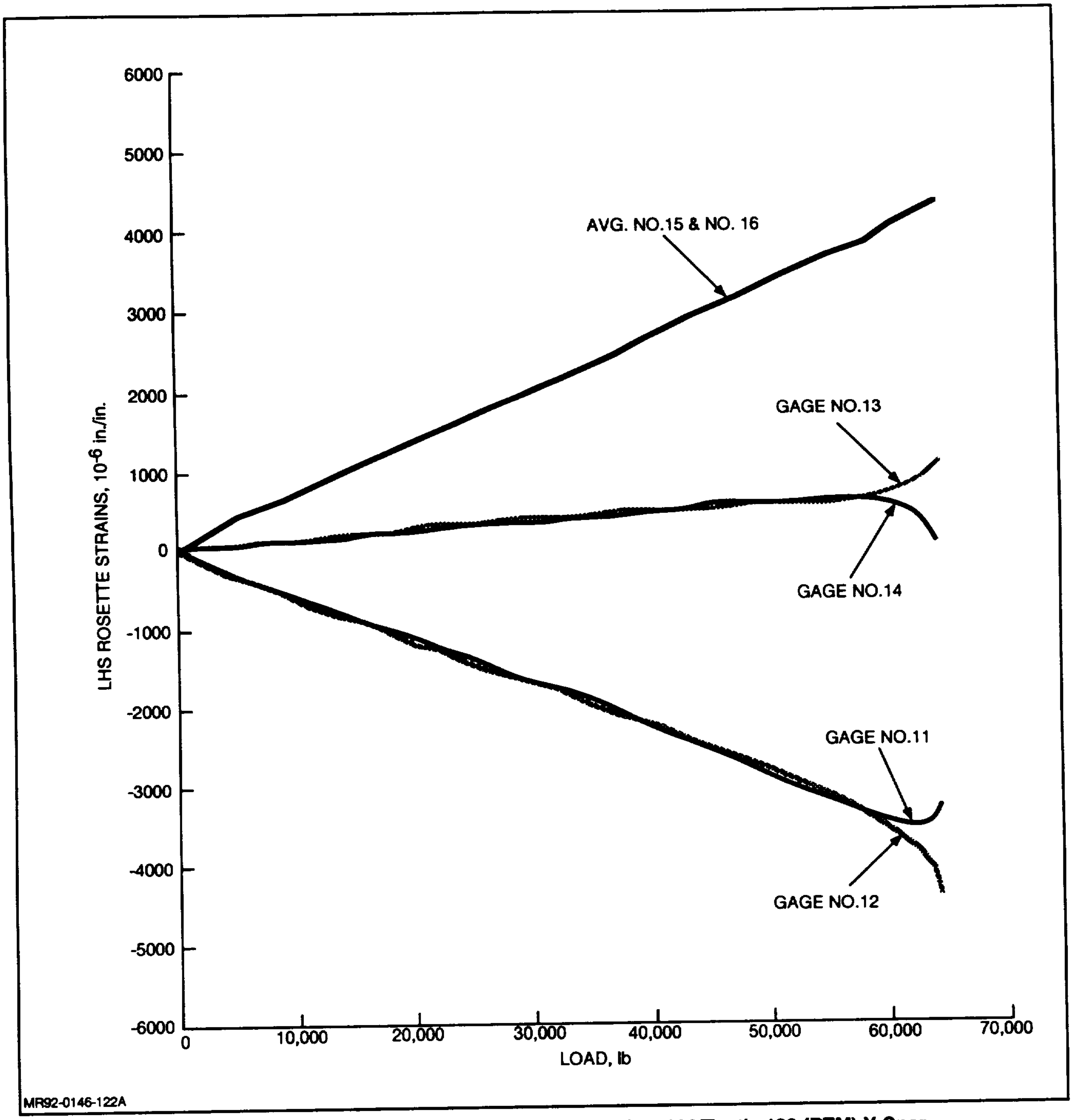

Fig. 72 LHS Rosette Strain on Side with Failure : G40-800/Tactix 123 (RTM) Y-Spar

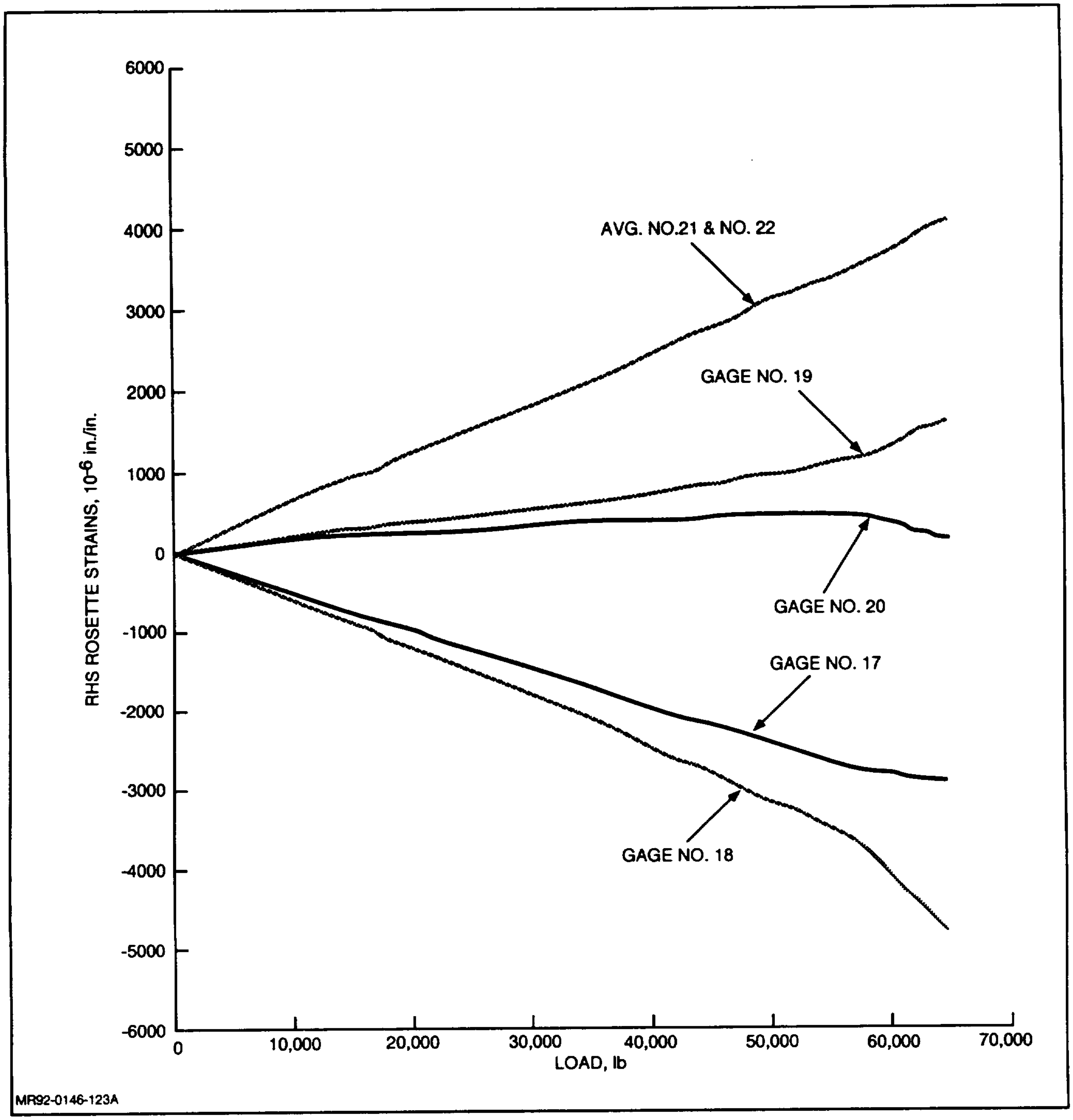

Fig. 73 RHS Rosette Strain on Unfailed Side : G40-800/Tactix 123 (RTM) Y-Spar

Fig. 74 "Y"-Spar in Test Fixture

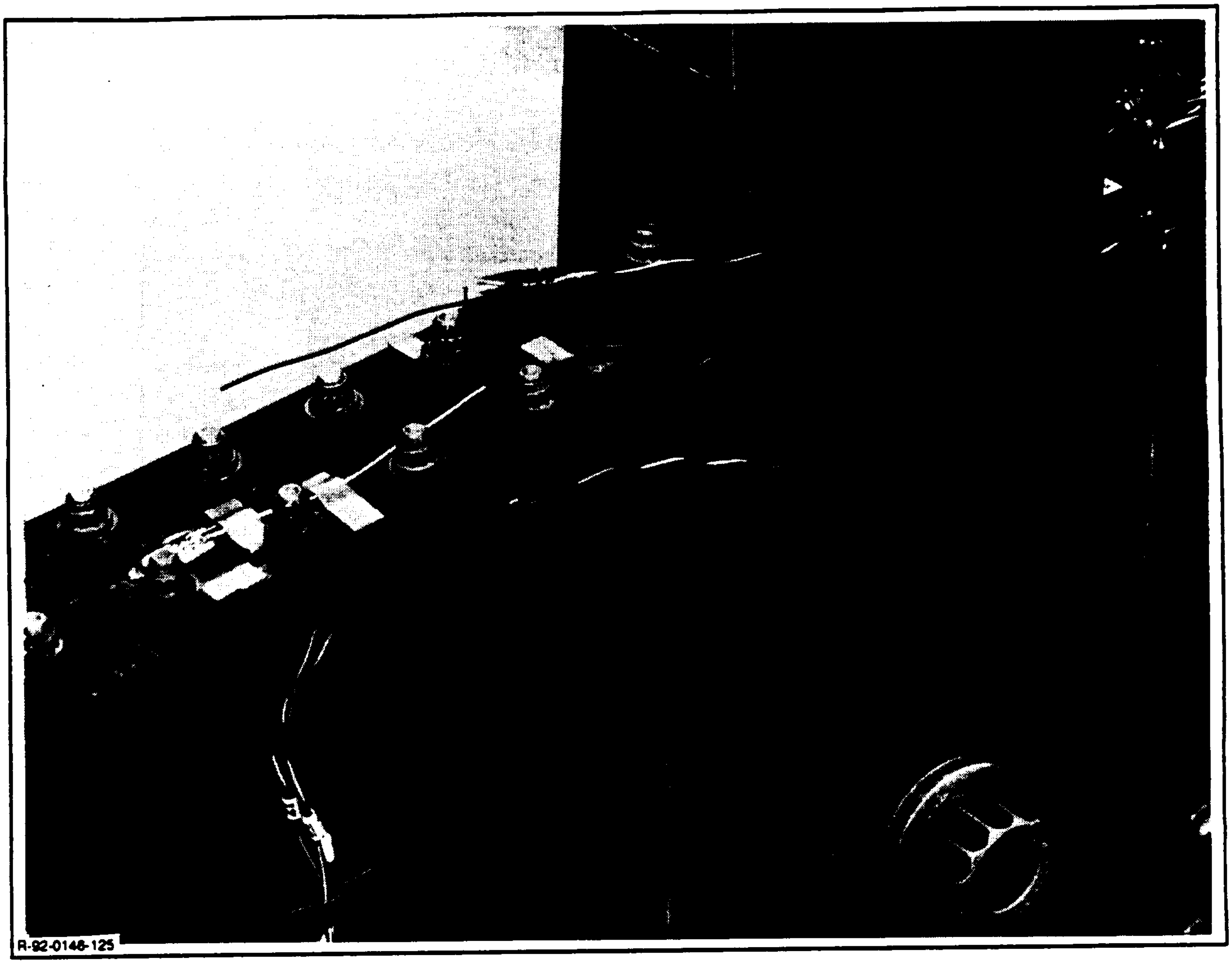

Fig. 75 Tension Failure of Cap of Woven IM7/3501-6 Gr/Ep RFI "Y"-Spar at 8, 470 μ in./in.

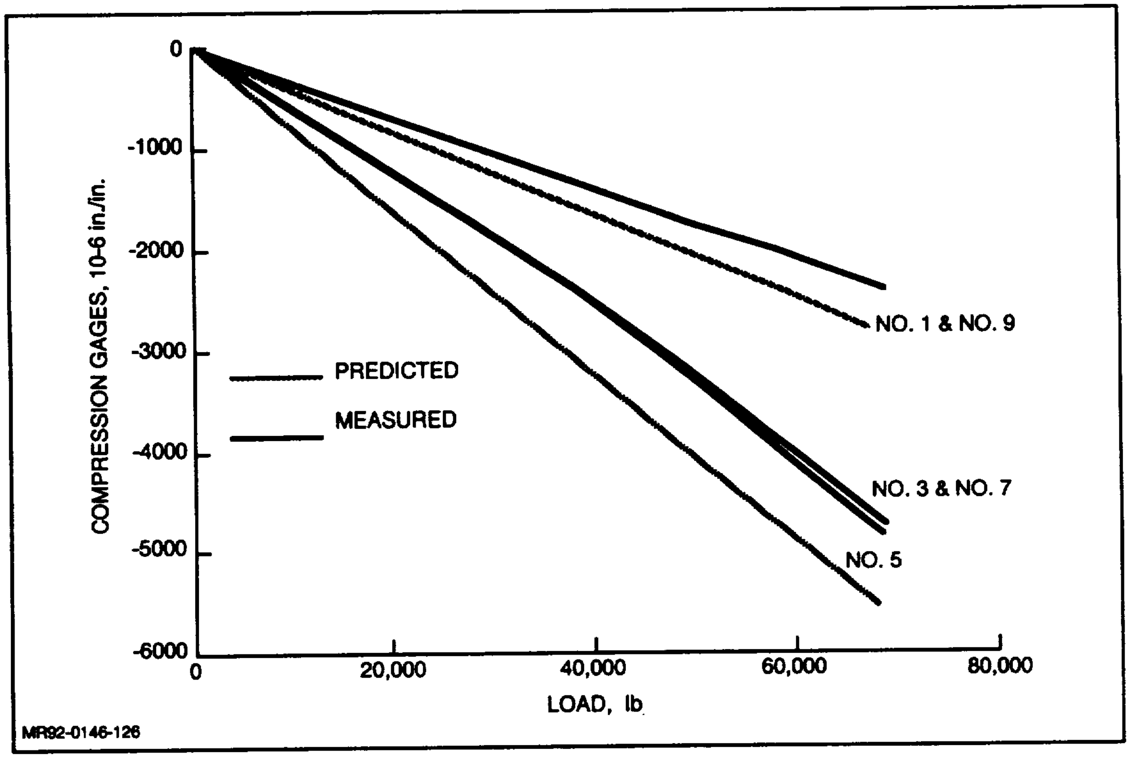

Fig. 76 Compression Strain vs Load: Woven/Stitched IM7/3501-6 Gr/Ep (RFI)

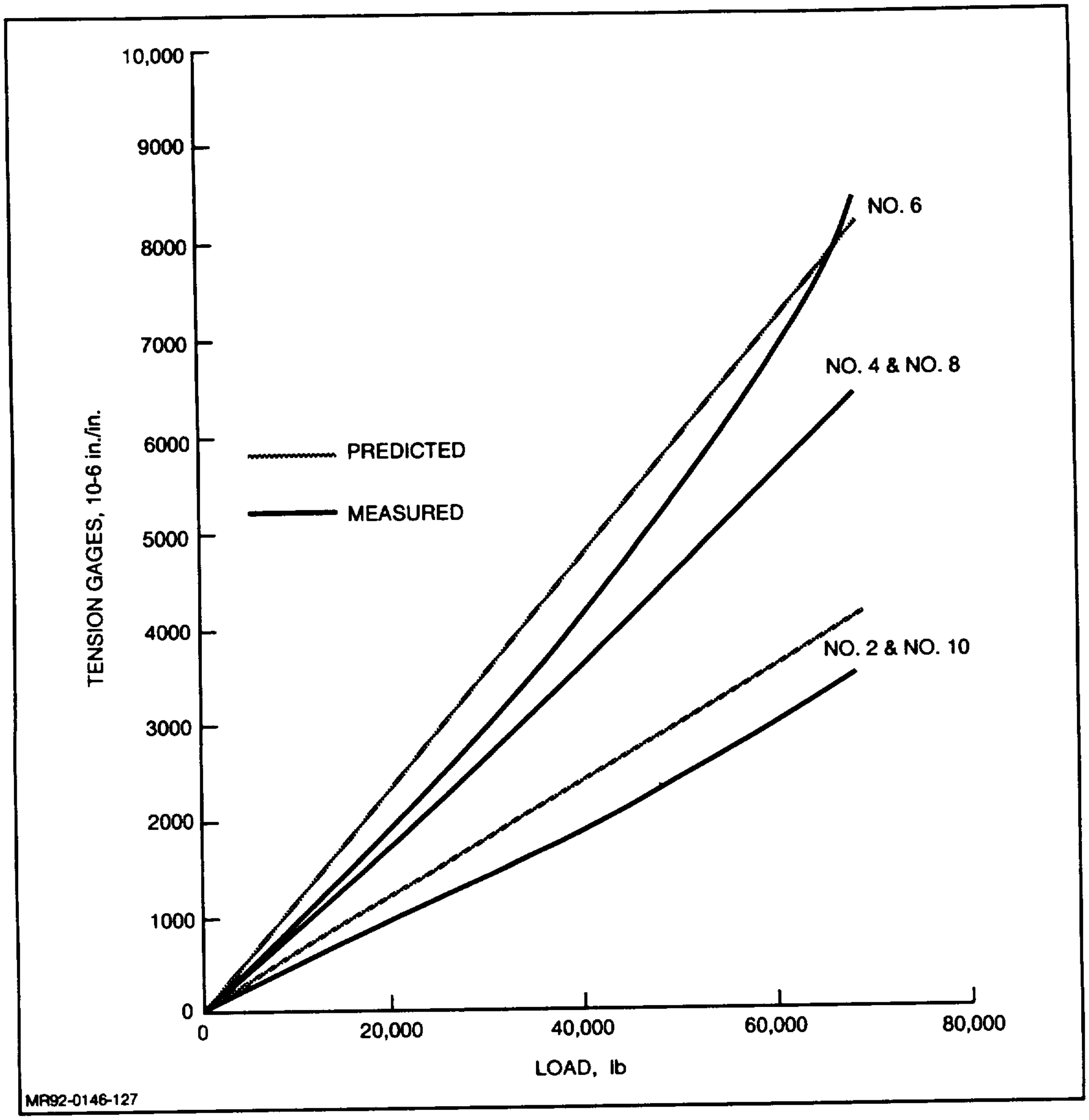

Fig. 77 Tension Strain vs Load: Woven/Stitched IM7/3501-6 Gr/Ep (RFI)

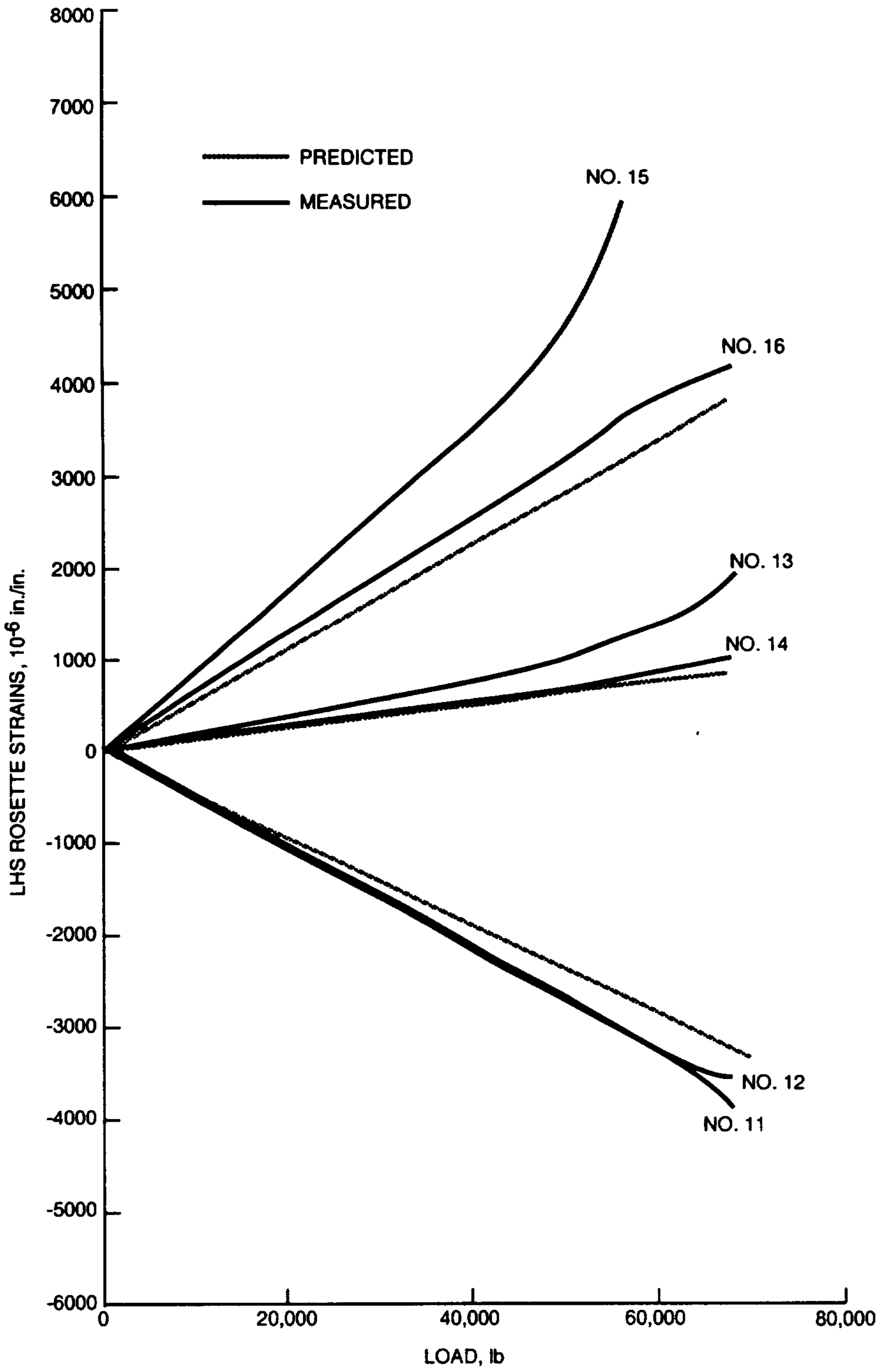

Fig. 78 LHS Rosette Strains vs Load: Woven/Stitched IM7/3501-6 Gr/Ep (RFI)

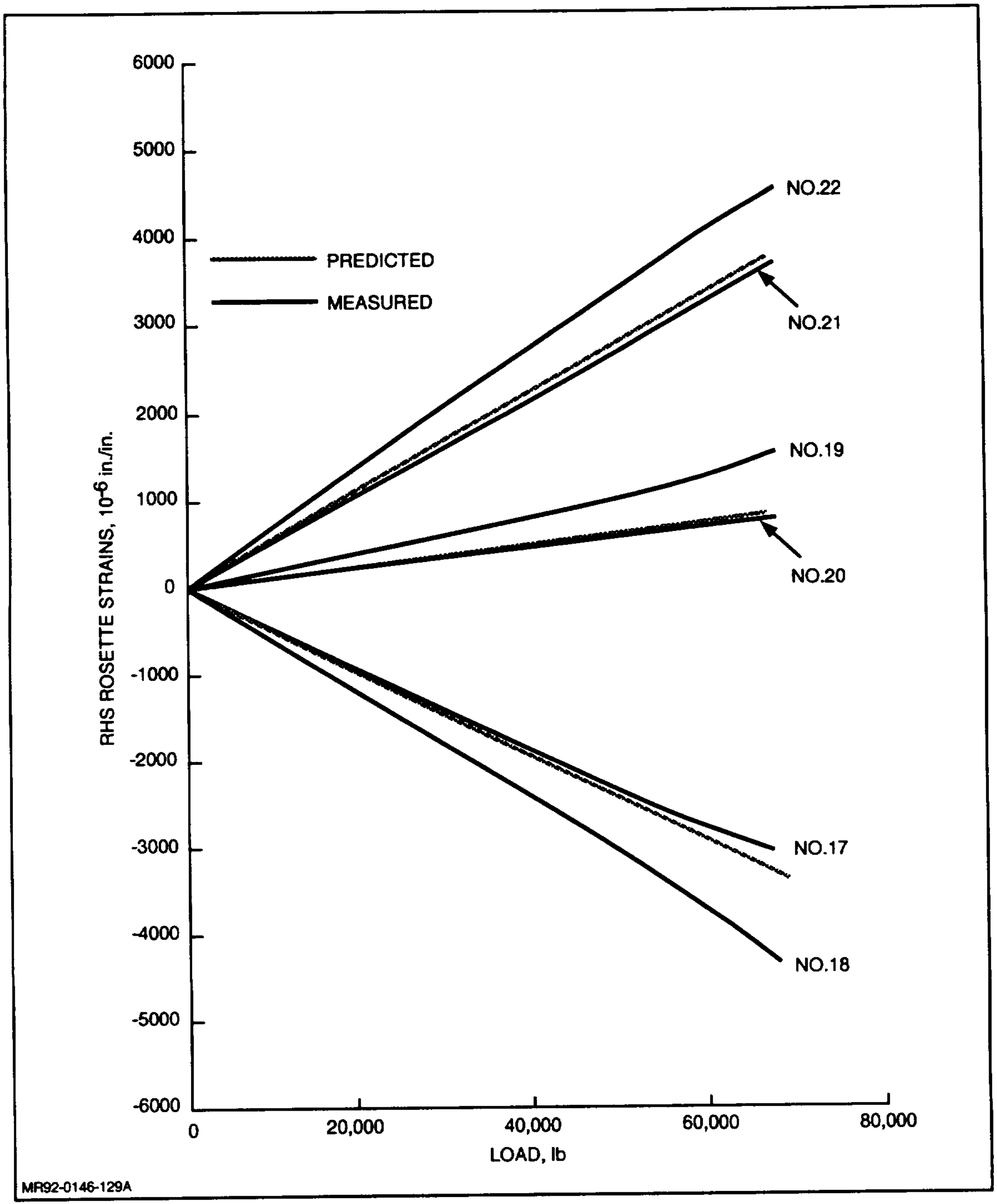

Fig. 79 RHS Rosette Strains vs Load: Woven/Stitched IM7/3501-6 Gr/Ep (RFI)

6 – SUBTASK 5: ASSESSMENT

6.1 STRUCTURAL ASSESSMENT

Based on a review of the failed test spars and the measured strains, some conclusions can be drawn regarding the structural viability of the different manufacturing approaches. In general, the measured strains agreed well with the predictions. This is significant when one considers that the stiffness properties were derived from unidirectional tape properties with corrections made for fiber volume and the woven nature of the preforms. Spar bending strains at failure were close to or exceeded ±6000 μin./in. in all cases. While only the G40-800/Tactix 123 test specimen failed due to the load in the spar itself, this failure compared well with the average predicted value for an IM6/3501-6 unidirectional tape prepreg laminate autoclave cured. A brief discussion of the structural aspects of each test spar is given below.

6.1.1 AS4/PEEK Commingled

Although this spar had problems during the preform fabrication, and the final product was oversize in height and thickness, its performance during the test was predictable. Figures 80 to 83 show measured and predicted strain versus applied load. Predictions are based on a 11.8/41/47.2% (0°/±45°/90°) laminate obtained from the results of coupon testing (Tables 47 and 48). Due to the increased thickness,

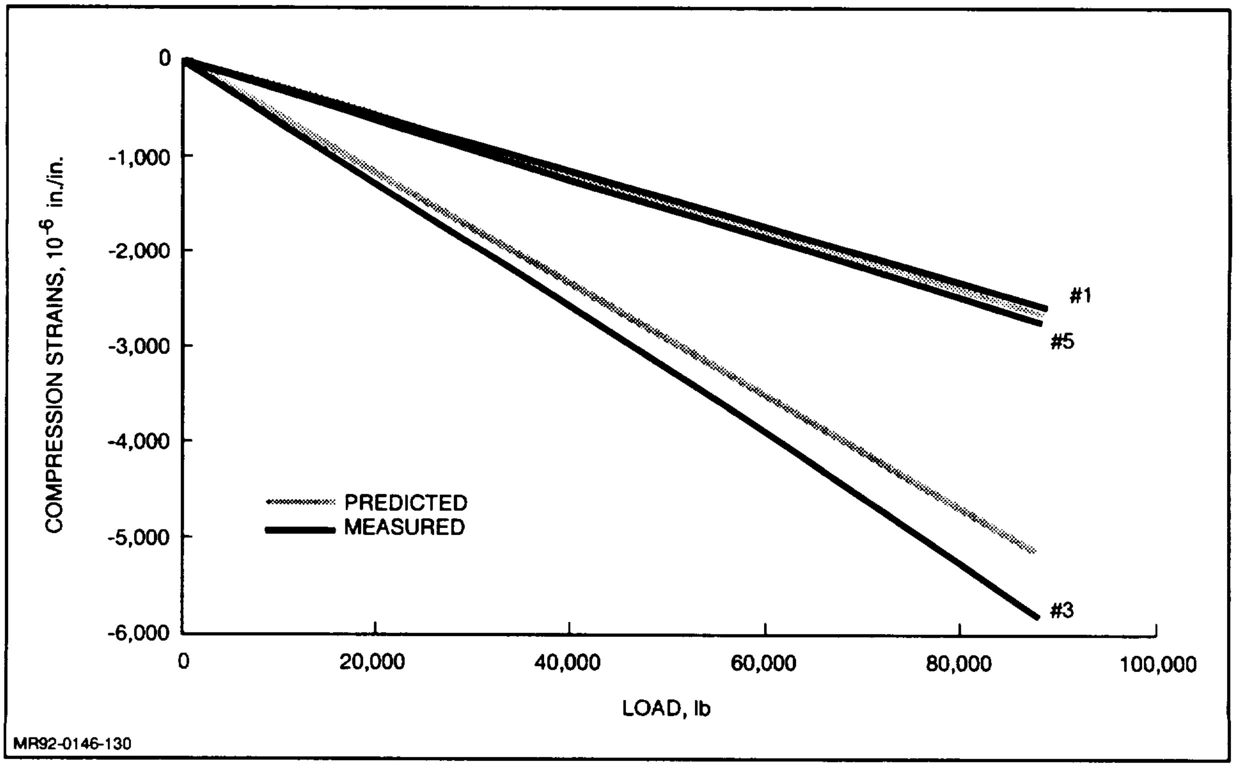

Fig. 80 Compression Strains vs Load : AS4/PEEK Commingled Y- Spar

web buckling and a web shear failure were precluded. Failure at an applied load of 89,000 lb occurred because the tensile load in the cap exceeded the open-hole strength. The bending strains at failure were +8270 μin./in. and -5940 μin./in., showing that this manufacturing approach met the program goal of ±6000 μin./in. in bending.

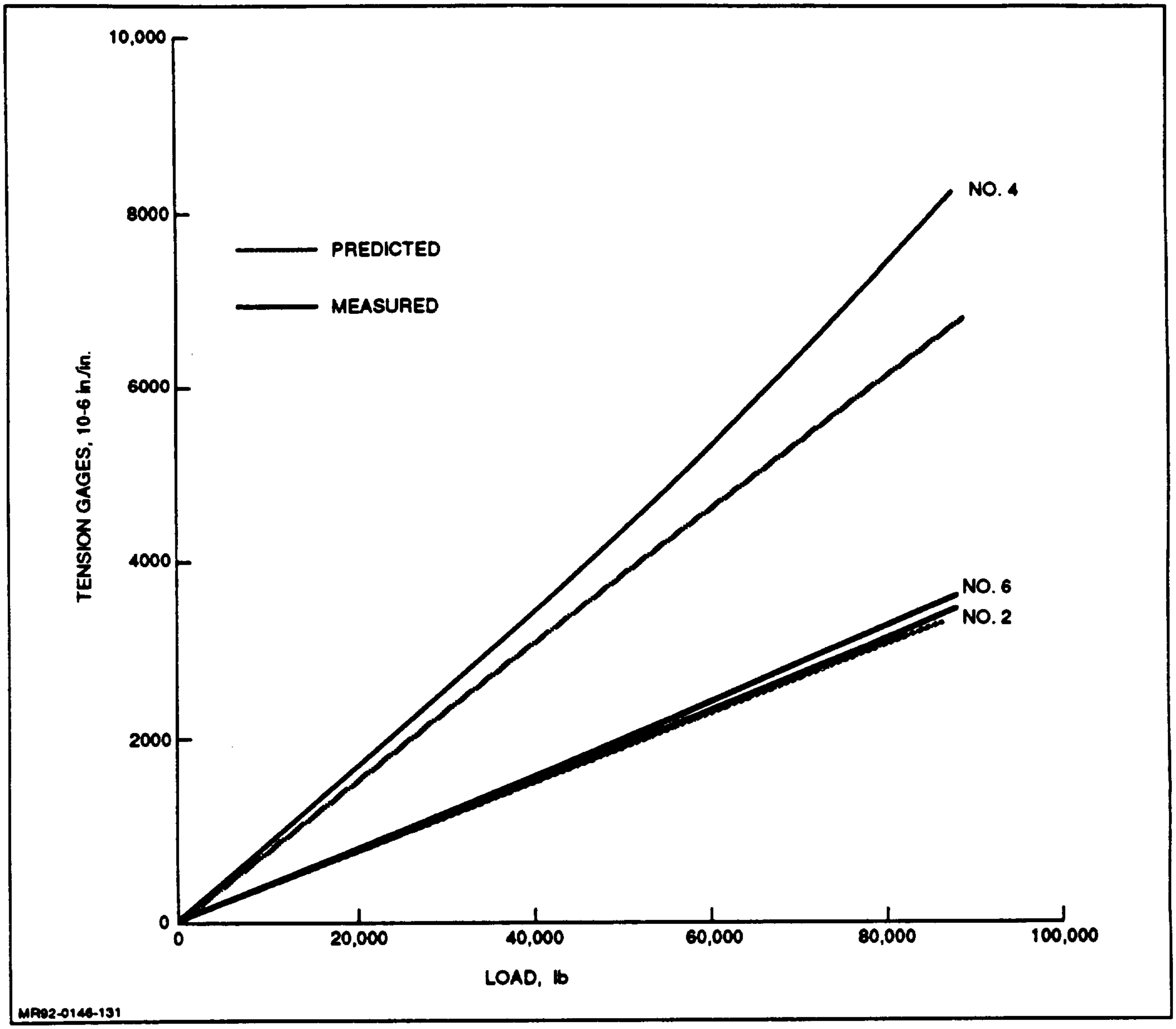

Fig. 81 Tension Strains vs Load: AS4/PEEK Commgled Y-Spar

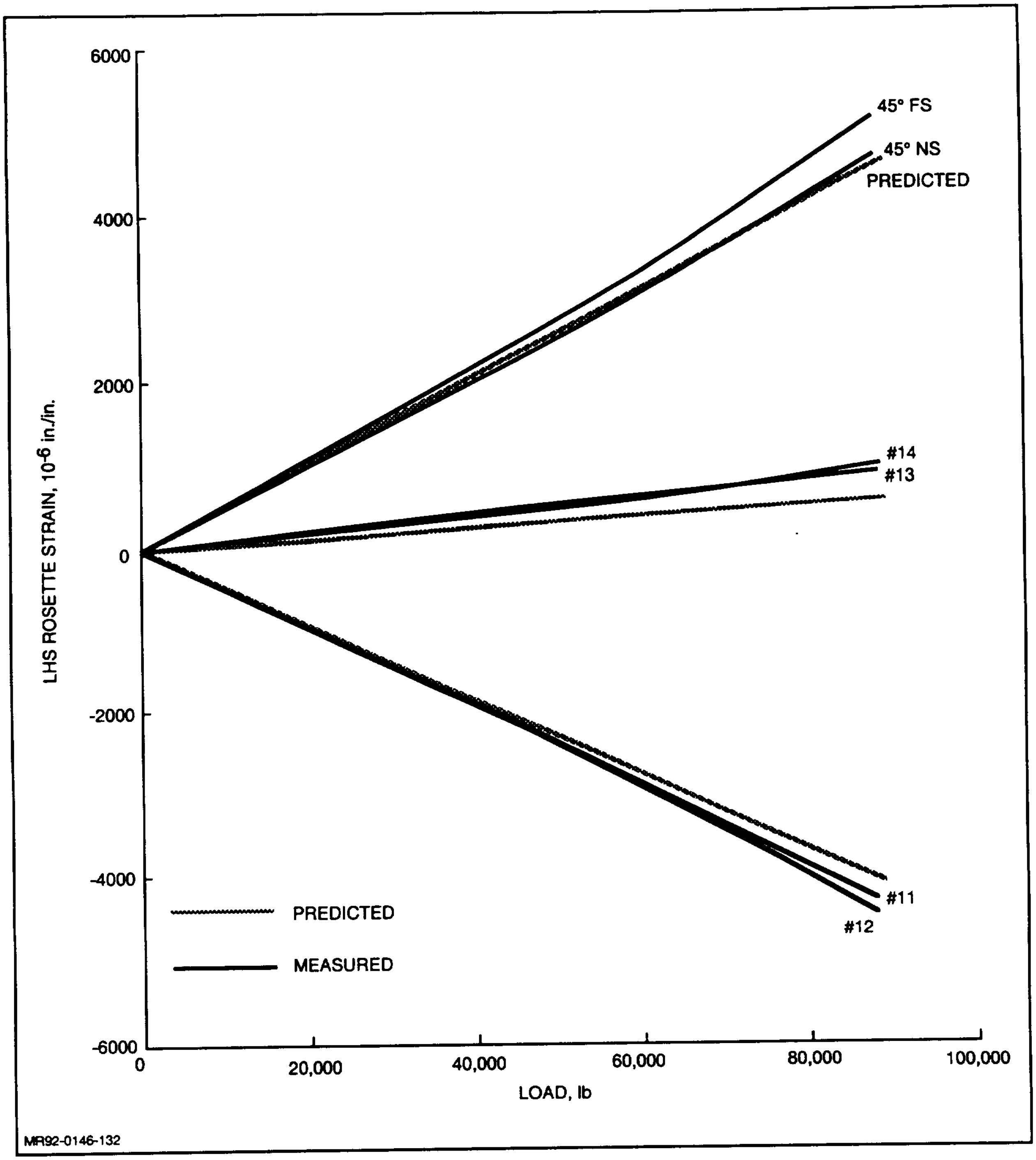

Fig. 82 LHS Rosette Strain vs Load: AS4/PEEK Commingled Y-Spar

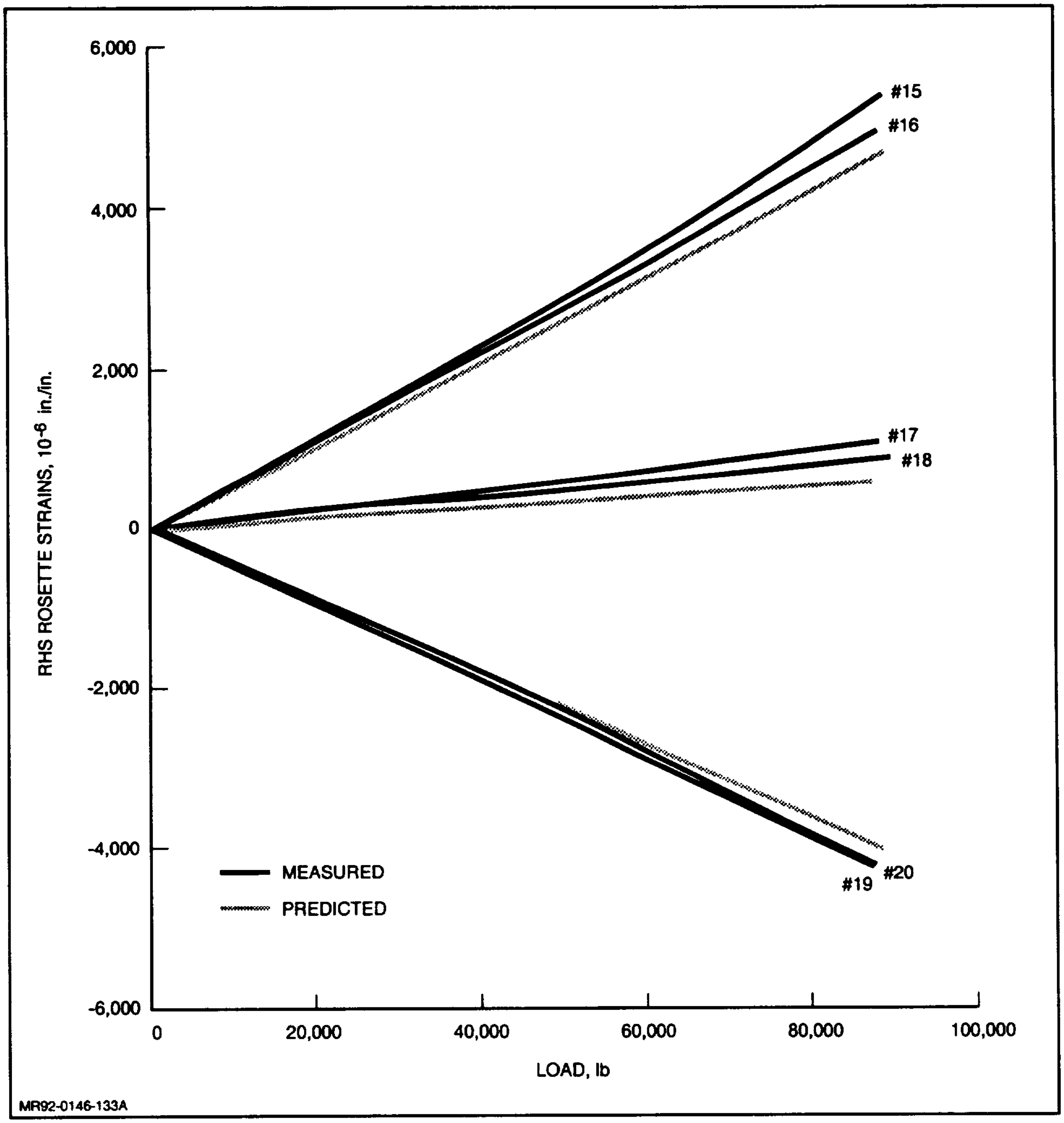

Fig. 83 RHS Rosette Strains vs Load: AS4/PEEK Commingled Y-Spar

6.1.2 G40-800/Tactix 123 (RTM)

The strain response of this spar is plotted in Fig. 84 to 87. While the bending strains are in good agreement with the predictions, the shear strain is higher than expected. This is probably because of a lower effectiveness of the surface plies as a result of surface dryness noted in the spar. Using the measured shear strain and the analytical shear flow implies an effective 0.120-in.-thick, 10/56/34% laminate as opposed to the 0.138-in.-thick, 9/62/29% laminate expected. This revised laminate has an Et of 0.704 x 10^6 lb/in. and a Gt of 0.440 x 10^6 lb/in., while the laminate used for pre-test analysis had an Et of 0.778 x 10^6 lb/in. and a Gt of 0.548 x 10^6 lb/in. As a result, the net change in bending stiffness is small while the change in shear strain is high. Web buckling occurred at an applied load of ~60,000 lb, or an average flat web shear flow of 2840 lb/in. Predicted buckling varies from 2070 lb/in. for simply-supported edge conditions to 3190 lb/in. for clamped edges. In both cases, a reduction in stiffness was taken for the surface plies only and the actual thickness was used. At the failure load of 65,300 lb, the calculated maximum shear stress in the web was 31,200 lb/in.^{2} on the effective thickness and normalized to 62% fiber volume. Compared to a design allowable for IM6/3501-6 prepreg tape of 27,000 lb/in.^{2} and an average strength of 33,750 lb/in.^{2}, the RTM process is considered structurally viable once provisions are made to ensure that all the fibers are rendered effective.

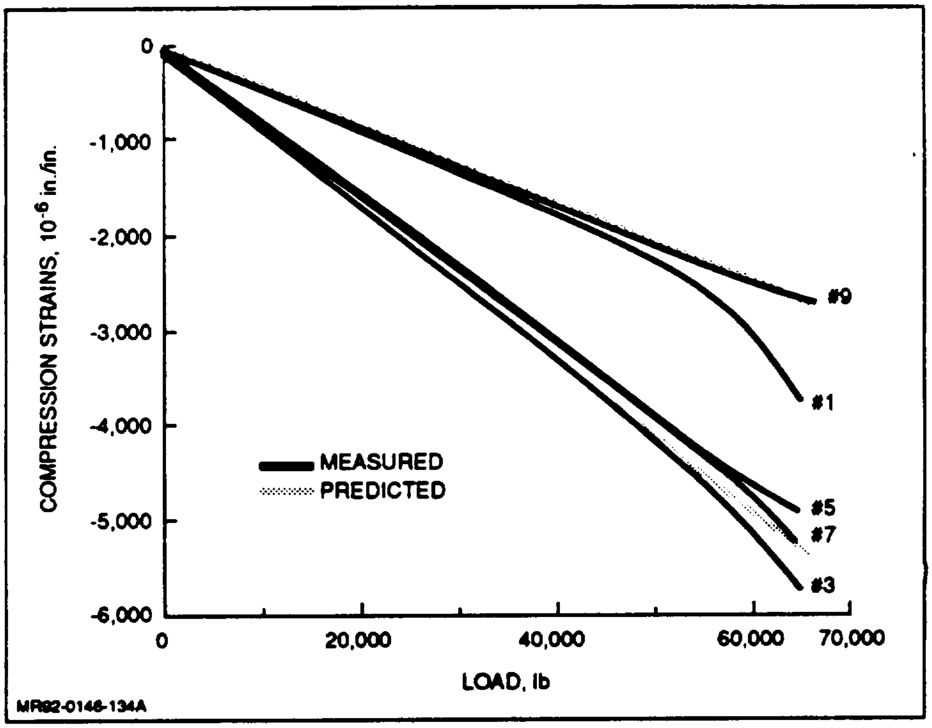

Fig. 84 Compression Strains vs Load: G40-800/Tactix 123 (RTM) Y-Spar

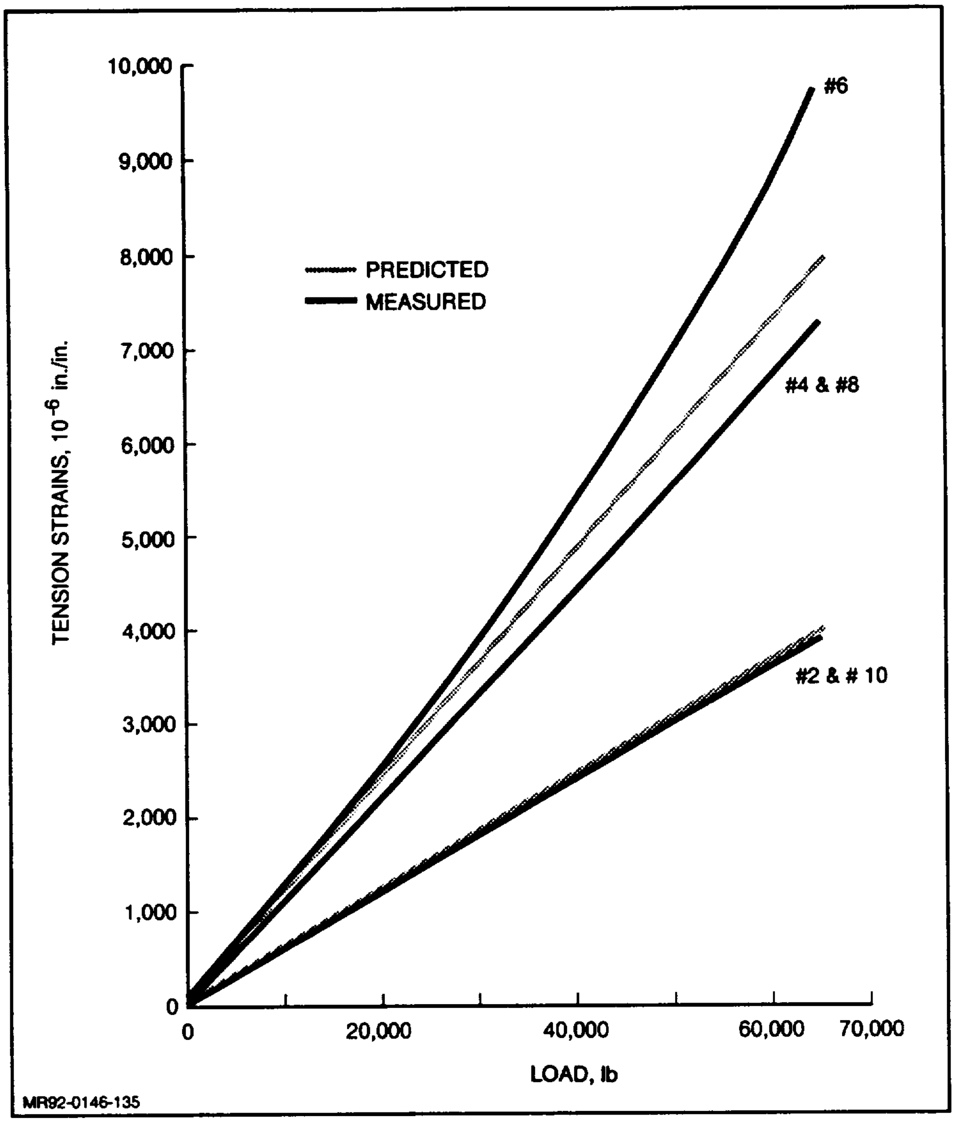

Fig. 85 Tension Strains vs Load: G40-800/Tactix 123 (RTM) Y-Spar

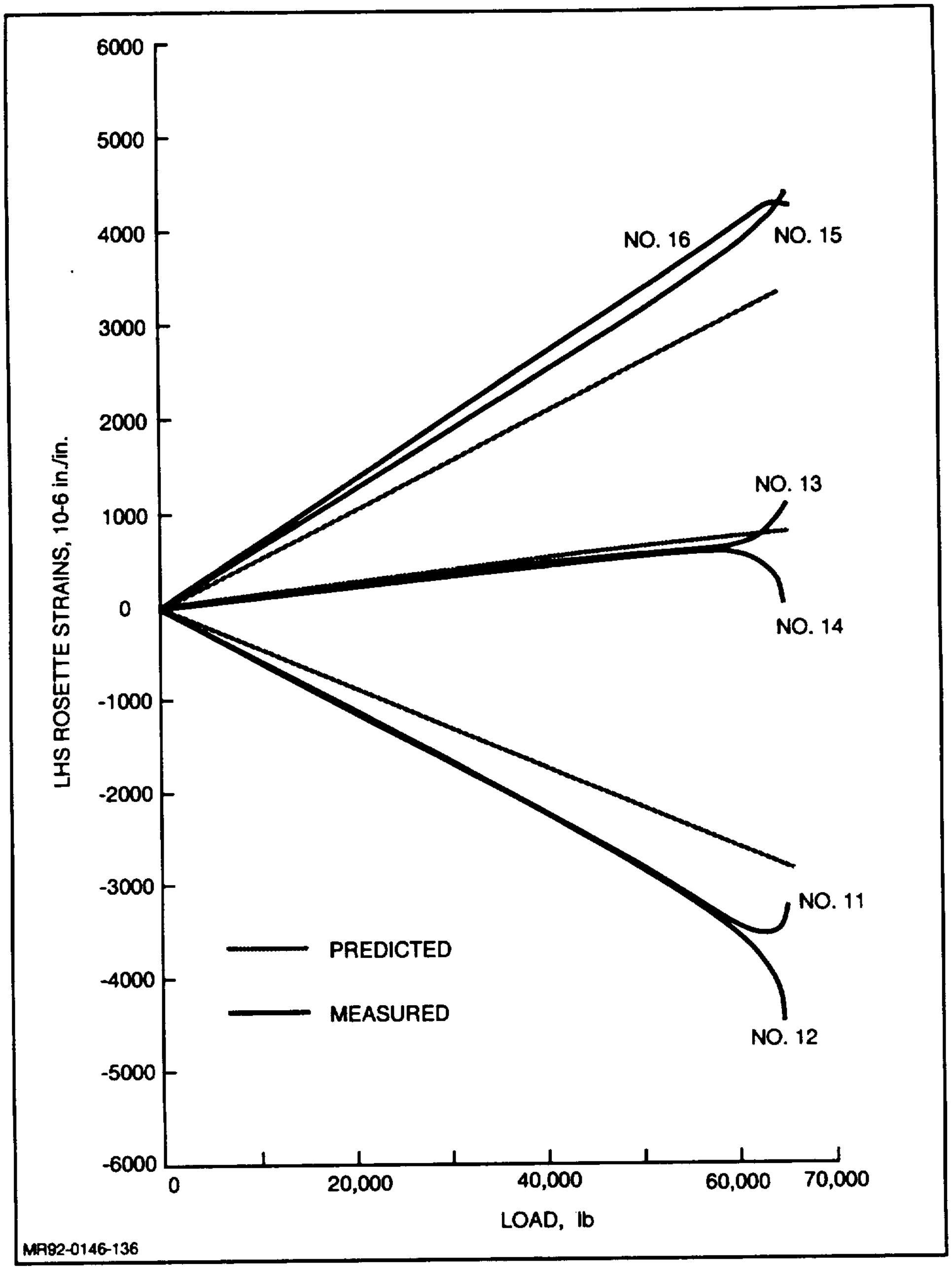

Fig. 86 LHS Rosette Strains vs Load: G40-800/Tactix 123 (RTM) Y-Spar

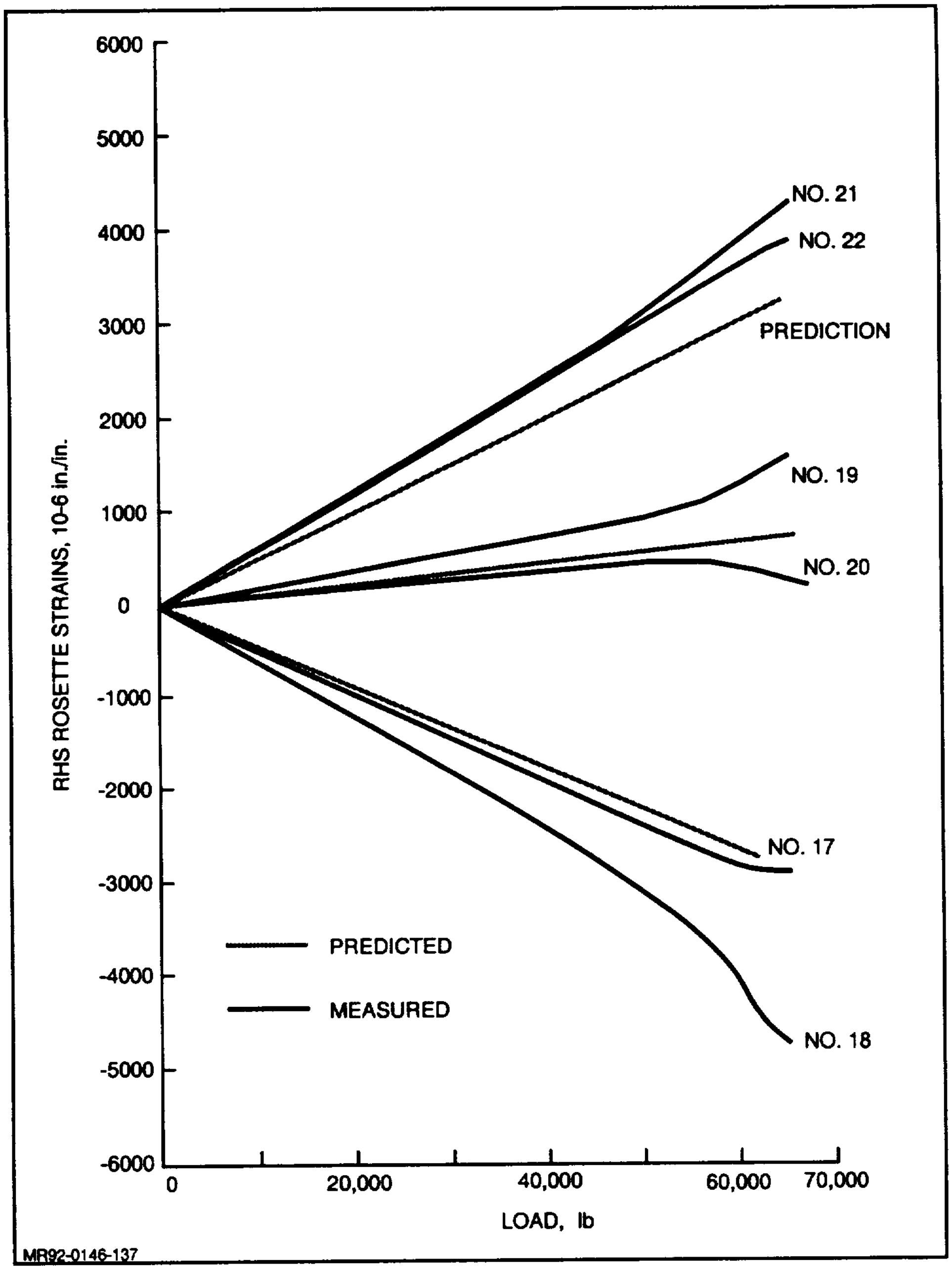

Fig. 87 RHS Rosette Strains vs Load: G40-800/Tactix 123 (RTM) Y-Spar

6.1.3 G40-800/3501-6 (RFI)

This spar performed very well as seen from the strain plots in Fig. 88 to 91. Buckling of the web occurred at ~70,000 lb of applied load or an average shear flow of 3320 lb/in. Analytical buckling predictions were 3530 lb/in. for simply-supported edges and 4780 lb/in. for clamped edges. Examination of the failed beam revealed that the stacking sequence of the web was not symmetric and hence the premature buckling. The test beam failed at an applied load of 76,000 lb due to local bending of the compression cap. At this load, the maximum calculated web shear stress was 36,540 lb/in.^{2} on the effective thickness and normalized to 62% fiber volume. Thus, the RFI process also proved to be a very structurally acceptable process.

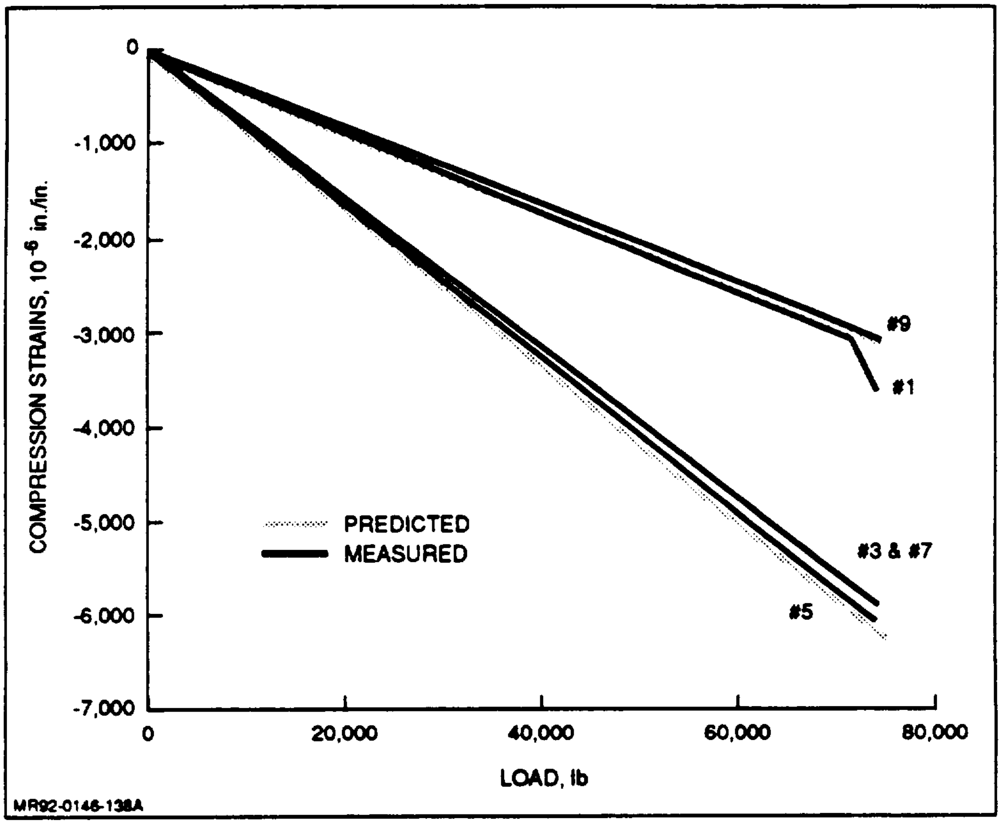

Fig. 88 Compression Strain vs Load: G40-800/3501-6 (RFI) Y-Spar

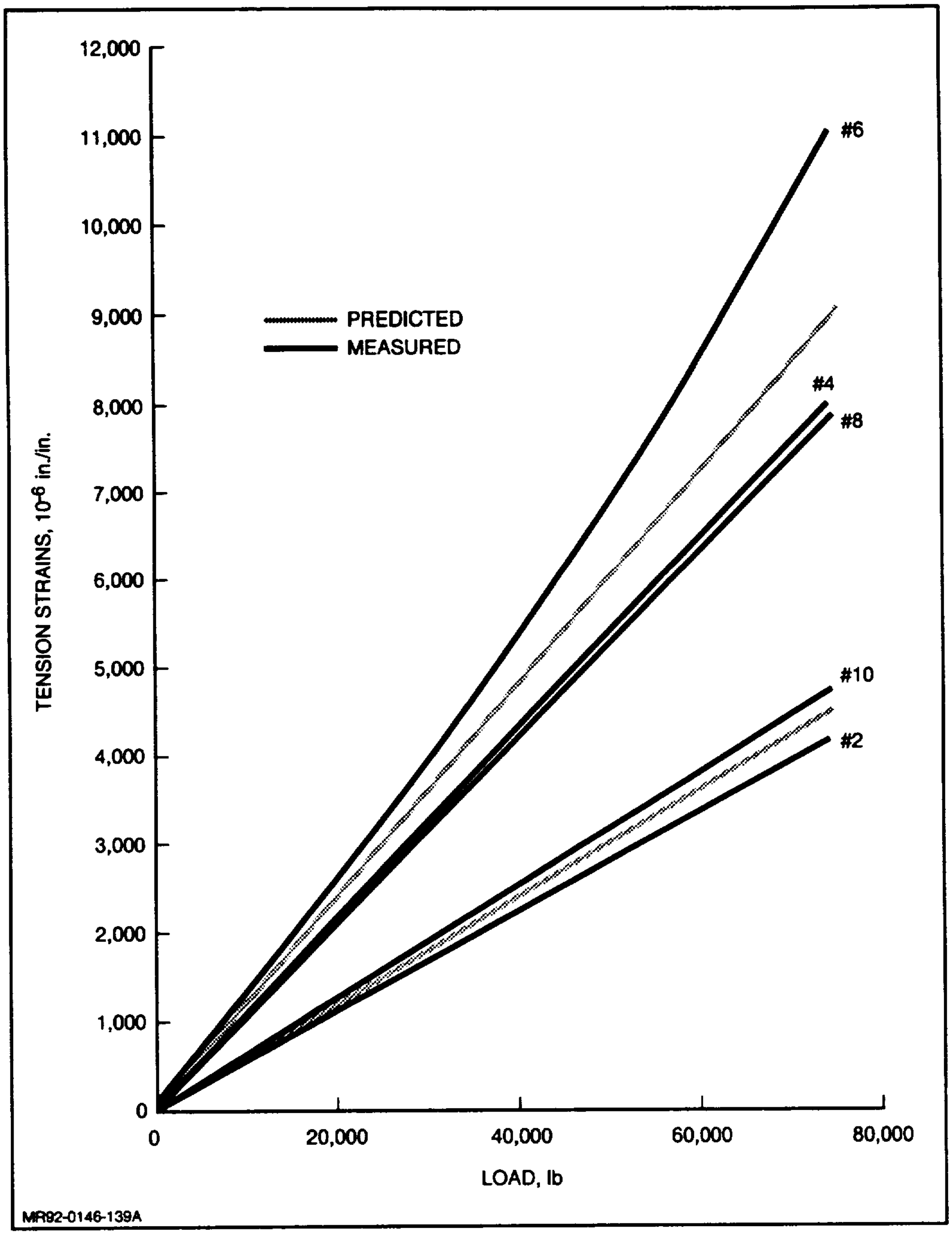

Fig. 89 Tension Strains vs Load: G40-800/3501-6 (RFI) Y-Spar

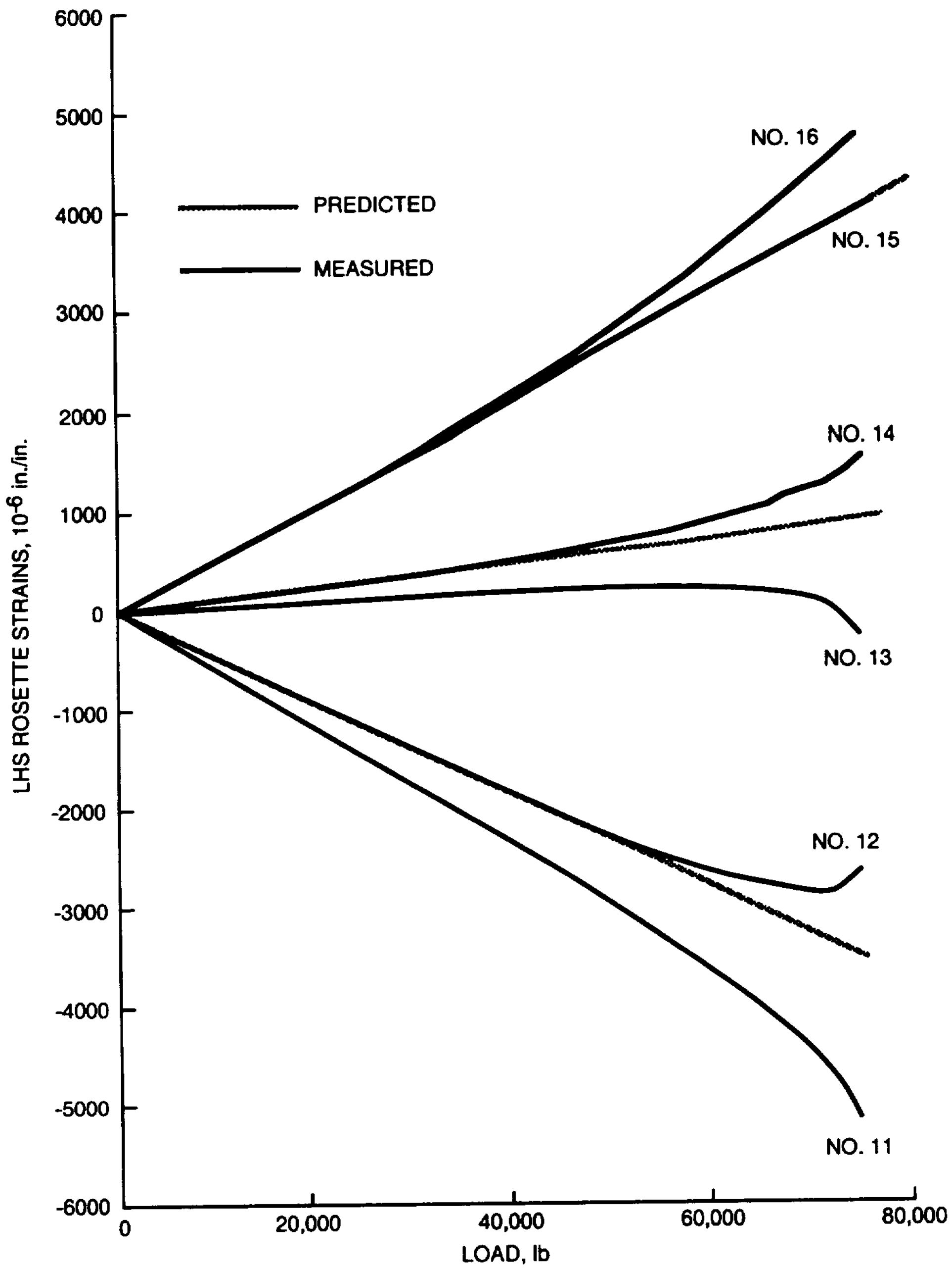

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Fig. 90 LHS Rosette Strains vs Load: G40-800/3501-6 (RFI) Y-Spar

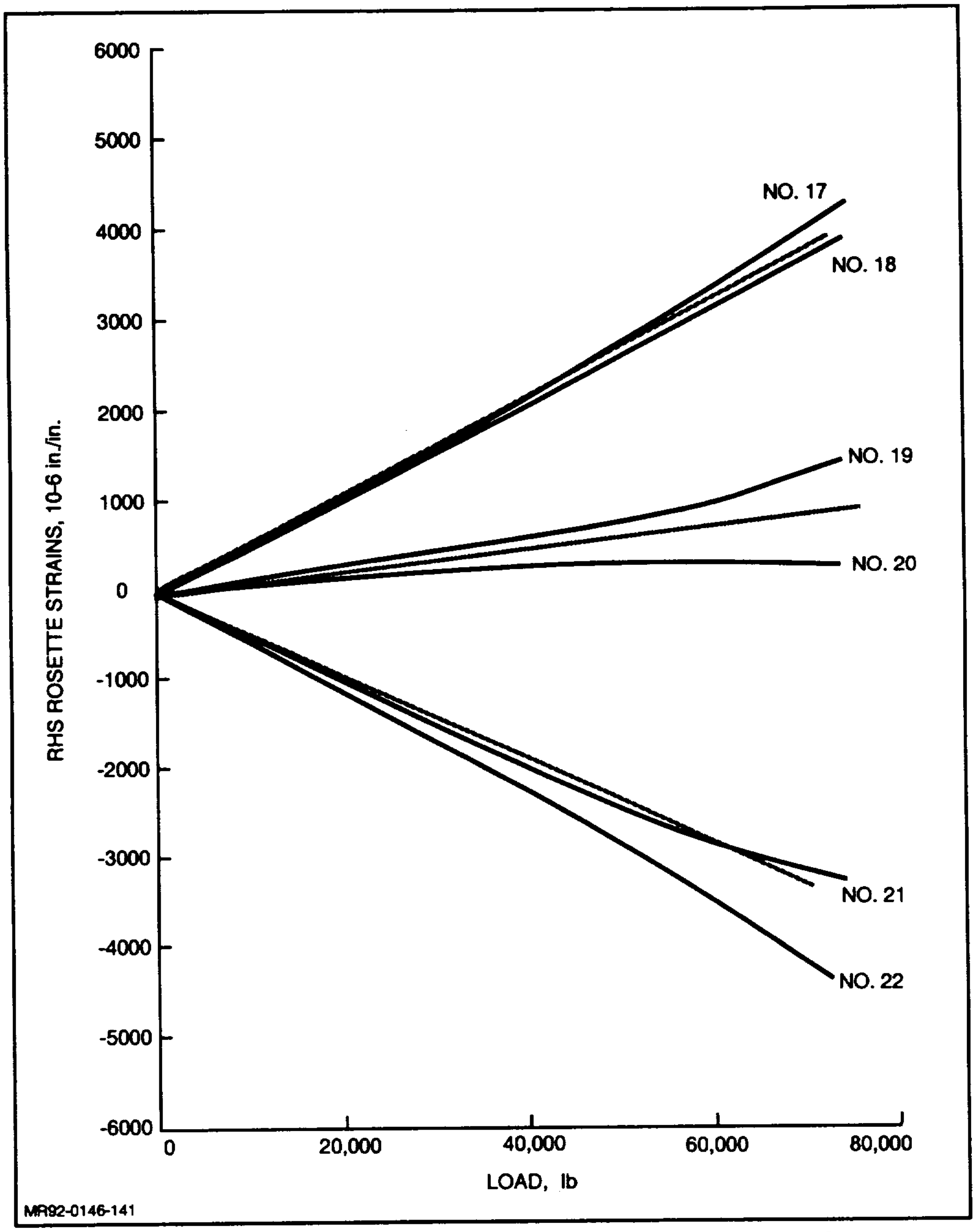

Fig. 91 RHS Rosette Strains vs Load: G40-800/3501-6 (RFI) Y-Spar

6.2 STRUCTURAL EFFICIENCY

The various material form/processing combination Y-spars were rated for their structural efficiency. As shown in Fig. 92, the knitted/stitched G40-800/3501-6 RFI Y-spar is superior to all the others in terms of failure load per spar weight. The worst performer is the woven AS4/PEEK commingled Y-spar, which was manufactured oversize. The knitted/stitched RFI spar also exhibited the highest ratio of web buckling to web area (Fig. 93) and the highest cap compression strain per unit weight, as shown in Fig. 94.

6.3 MANUFACTURING ASSESSMENT

Based on the results of the manufacturing effort, from both cost and technical standpoints, the following discussion will provide a basic assessment of the fabrication approaches and will touch on the competing material forms as well. As is generally the case, each technique brings with it a set of good points and bad points; therefore, determining a single "ideal" process necessarily involves tradeoffs among these characteristics.

6.3.1 Autoclave Consolidation

Regardless of the particular materials involved when dealing with a carcass or preform, there is a considerable bulk factor associated with the material prior to processing. This results in the need for significant compaction during the autoclave cycle. Although some compaction occurs at room temperature under vacuum bag pressure alone, most occurs in the autoclave at elevated temperature and high fluid pressure.

Consequently, tooling for this approach must not only accommodate the bulky preform prior to processing, but also must be capable of yielding the final part dimensions and thicknesses after processing. As noted in the lengthy technical discussion earlier, this was found to be a difficult challenge. Even with the limited three-dimensional nature of the "Y"-spar's configuration, controlling the thicknesses and symmetry of the finished part was not possible with total consistency and tight tolerances. The final results were highly dependent on the quality of the vacuum bagging operation and other processing parameters not easily, or repetitively, controlled.

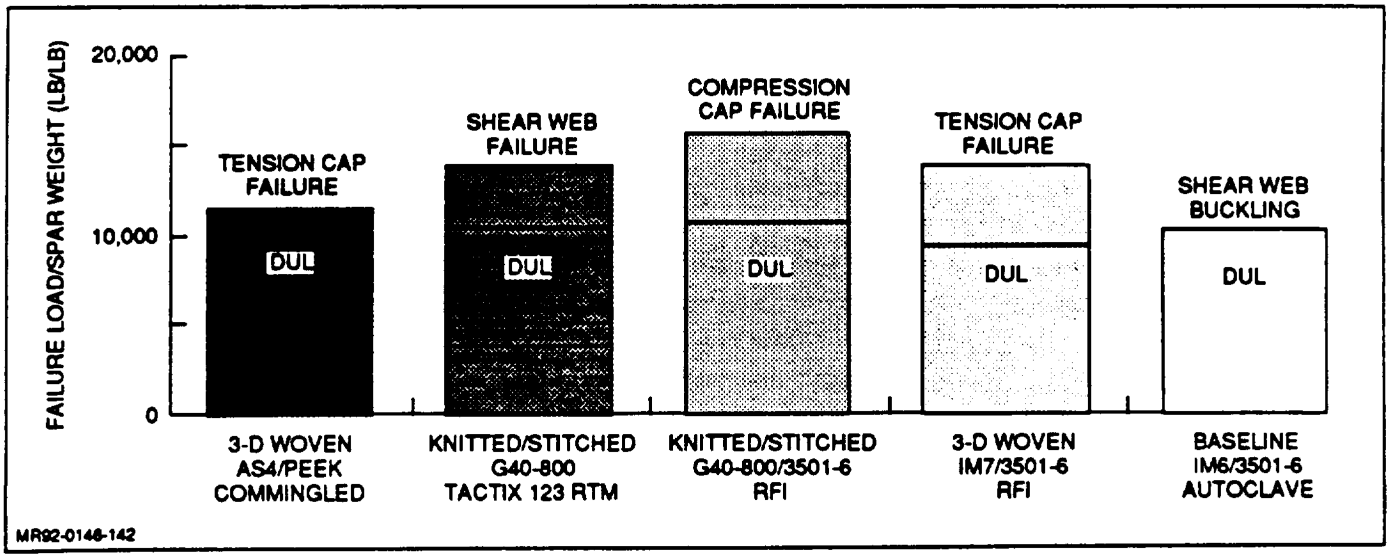

Fig. 92 Y-Spar Failure Load per Unit Weight

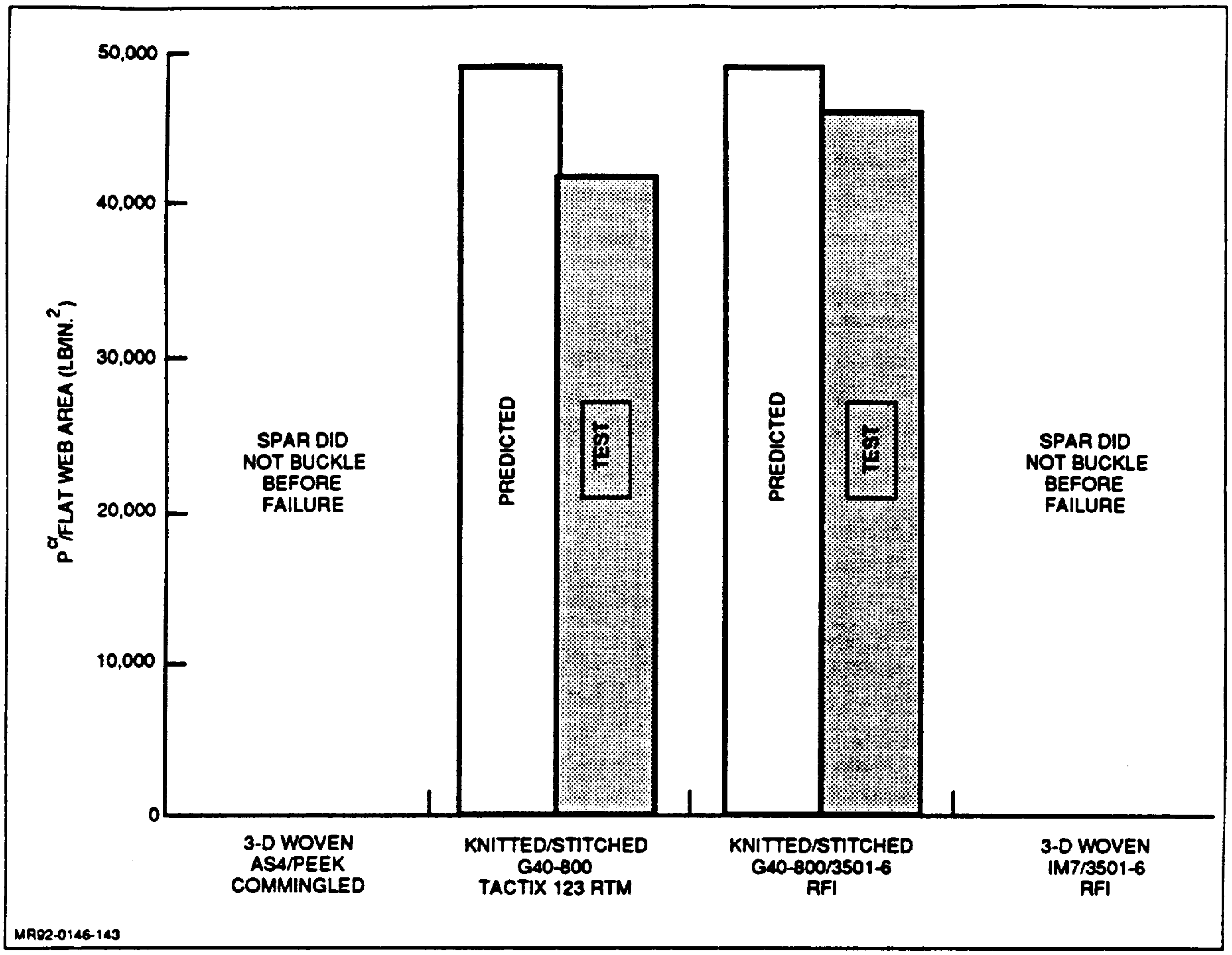

Fig. 93 Y-Spar Web Buckling

Another technical problem associated with autoclave processing, particularly at the high temperatures demanded by thermoplastic materials, is the long cycle times required to heat large, high-mass tools completely. Although the autoclave's heating capabilities could be supplemented by integral heaters incorporated in the tooling, this approach was not possible within the scope of this program.

A final technical consideration is that parts produced in an autoclave generally require a trimming operation, after processing, to yield final part dimensions. This is a labor-intensive activity, particularly as part complexity increases, as is the case with subsequent tasks in this program.

Factoring in the cost data presented previously essentially eliminates autoclave consolidation from further consideration in the program's remaining fabrication efforts.

6.3.2 Resin Transfer Molding (RTM)

Although as with autoclave consolidation the bulk factor of the preform is still a concern in RTM, it is lessened by the fact that the preform in RTM is dry fabric only. Therefore, it should be possible – even with relatively high fiber volume fractions – to completely close the tool's details around a preform

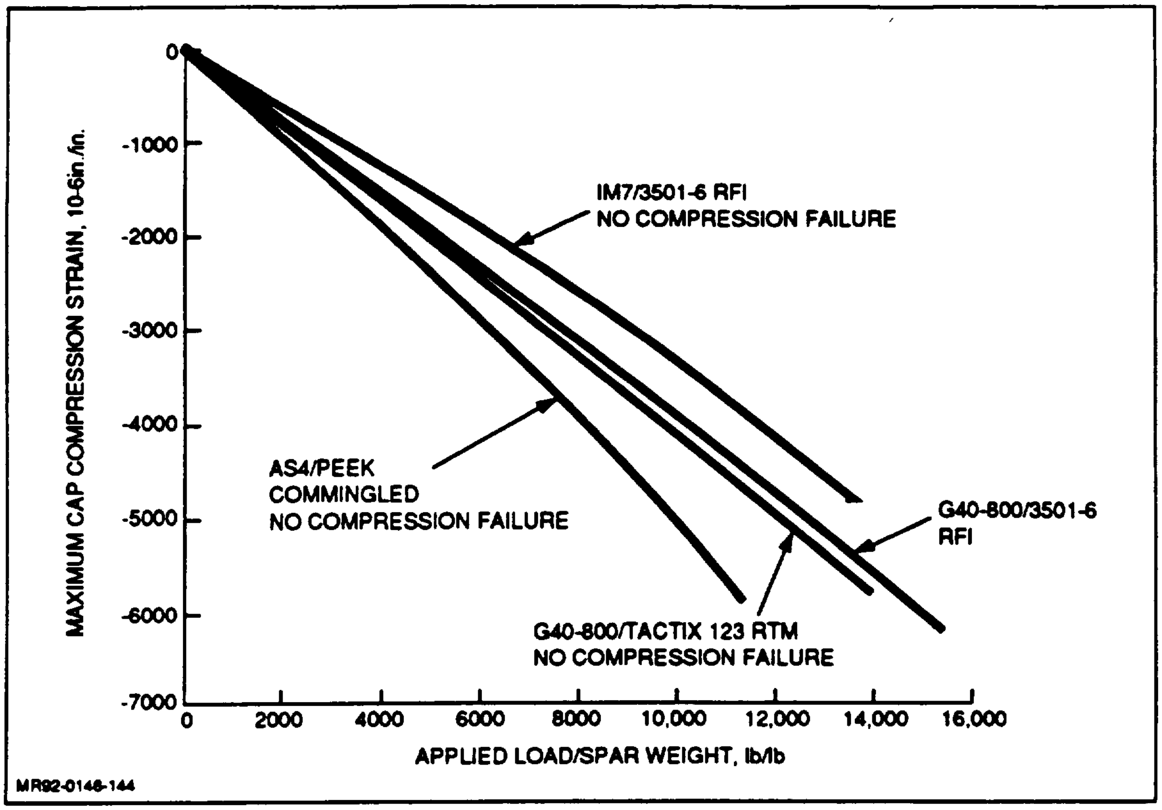

Fig. 94 Compression Strain vs Applied Load

prior to resin injection. There is, however, still some minimal trimming of the preform that is required during part loading.

A primary advantage to the RTM process is the ability to create a finished, net-trimmed part in one operation. There is generally some peripheral resin richness in an RTM-processed part, but this condition can be minimized with careful pre-trimming during loading in the tool.

Since, by definition, RTM tooling is essentially matched dies, it is necessarily more expensive than equivalent tooling for autoclave use. Further additional tooling costs are associated with the need for seals, sprues, risers, gates, etc, that are inherent in the process.

Although most of the resulting parts fabricated via RTM for Task 1 were only partially successful for a variety of reasons, further examination of the process and its intricacies is warranted. This is particularly the case since the two D19B8220-11 parts failed due to improperly sized preforms, rather than due to any difficulty with the RTM process itself. In fact, despite the failed "0"-ring seal during injection of the knitted/stitched preform (-15), the part's overall quality was quite good – enough so for it to be successfully tested as a beam in four-point bending.

From a cost standpoint alone, the RTM process is quite a viable alternative. The raw results highlighted in the cost section show that it is somewhat more costly than RFI/autoclave processing (of the knitted/stitched preform). However, lowering the preform cost – by changing its fabrication process – brings the cost down to an even more competitive level, below that of the RFI/autoclave-processed woven spar.

6.3.3 Resin Film Infusion (RFI)/Autoclave Processing

As mentioned earlier, the RFI process was developed by Xerkon prior to their being absorbed into Compositek Corp., a subsidiary of Shell Oil. Although from a purely technical standpoint this process merits serious consideration, it appears that Compositek is not providing the level of support necessary to keep the process viable. In fact, it seems likely that Compositek is seeking to sell the process. What this means in terms of future technical support and assistance is not known.

Looking at the cost data presented earlier, the process is unquestionably superior to the others (for the knitted/stitched preform). However, as mentioned above, it should be noted that the knitted/stitched preform offers advantages to the processing that deflate the apparent cost of the part relative to the cost of using a woven/stitched preform. If this type of preform is not satisfactory from a structural point of view (i.e., a 3-D preform is required), then the true cost surpasses that of the RTM-processed spars, advancing relative cost-effectiveness.

6.3.4 Overall Manufacturing Assessment

The preceding dialogue provides the basis for the following overall recommendation of the preferred fabrication method.

Among the four alternatives, the Resin-Film-Infusion (RFI) process, with the knitted/stitched preform, provides the best balance of risk and cost to implement. Therefore, at the present time this is the recommended manufacturing approach for subsequent manufacturing tasks of this program.

6.4 COMPARISON OF COST AND STRUCTURAL EFFICIENCY OF VARIOUS Y-SPARS

From the above structural and manufacturing assessment, together with the projected cost data generated in Subsection 4.3, a comparison was made of the four material and process combinations Y-spars versus a standard Gr/Ep tape Y-spar autoclave cured. Table 51 shows the comparison. In overall performance the knitted/stitched RFI/autoclave processed Y-spar is rated best (highest structural efficiency and 20.9% cost savings). The second best is the knitted/stitched preform/RTM processed (second best structurally and 17.0% cost savings over the baseline).

TABLE 51 COMPARISON OF COST AND STRUCTURAL EFFICIENCY OF VARIOUS Y-SPARS

	PREFORM/PROCESSING COMBINATIONS				
	STANDARD TAPE/ AUTOCLAVE	KNITTED & STITCHED RTM	WOVEN & STITCHED/ AUTOCLAVED (TP)	KNITTED STITCHED/ RFI/ AUTOCLAVED	WOVEN & STITCHED/ RFI/ AUTOCLAVED
COST, $	12,900	10,712	14,319	10,200	13,091
SAVINGS OVER STANDARD, %	0.0	+ 17.0	− 11.0	+ 20.9	− 1.5
STRUCTURAL EFFICIENCY (1 IS BEST)	–	2	4	1	3

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7 – CONCLUSIONS

The study conducted as herein described has led to the following various conclusions:

- Textile Polymer Matrix Composites (PMC) can be designed and fabricated for primary aircraft structural components with equivalent efficiency and reduced acquisition costs compared with current-day PMC components (approximately 20% reduction)
- The various PMC materials, along with various processing methods, are all suitable for wing spar applications and thus provide for design/manufacturing flexibility
- Although the various processes have not yet been developed to a fully reliable state, with continued study it appears that full-scale components could be production-implemented in the future.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1996

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
Novel Composites for Wing and Fuselage Applications,
Task 1 – Novel Wing Design Concepts

5. FUNDING NUMBERS
Contract NAS1-18784
WU 505-63-10-10

6. AUTHOR(S)
J. A. Suarez, C. Buttitta, et al.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Northrop Grumman Corp., Inc.
Advanced Technology & Development Center
Bethpage, New York 11714-3595

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-198347

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: H. Benson Dexter
Final Report

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 24
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Design trade studies were conducted to arrive at advanced wing designs that integrated new material forms with innovative structural concepts and cost-effective fabrication methods. A representative spar was selected for design, fabrication, and test to validate the predicted performance. Textile processes, such as knitting, weaving, and stitching, were used to produce fiber preforms that were later fabricated into composite spars through epoxy Resin Transfer Molding (RTM), Resin Film Infusion (RFI), and consolidation of commingled thermoplastic and graphite tows. The target design ultimate strain level for these innovative structural design concepts was 6000 μin/in. The spars were subjected to four-point beam bending to validate their structural performance. The various material form/processing combination Y-spars were rated for their structural efficiency and acquisition cost. The acquisition cost elements were material, tooling, and labor.

14. SUBJECT TERMS
Woven, knitted/stitched textile preforms. Y-spars. Commingled preforms.
Resin transfer molding. Resin film infusion. Consolidation forming.

15. NUMBER OF PAGES
146

16. PRICE CODE
A07

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102